PEG-HOLE ASSEMBLY;

AN INVESTIGATION INTO TACTILE METHODS

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This is not the end.

It is not even the beginning

of the end.

But it is, perhaps,

the end of the beginning.

Winston Churchill, 1942.

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ABSTRACT

The search for a flexible automatic assembly machine for industry has involved researchers in the quest for a man-like robot. Extensive work is being done in the fields of visual feedback and pseudo-human tactile sensing. Is this artificial man with its complex automata theory and reliance on high computer usage necessary? Or perhaps a lower degree of intelligence, supported by well designed peripherals, will enable a 'robot' to perform its assembling tasks. It is in this mid-range between the extremes of a simple pick-and-place machine and a fully flexible, highly complex, and costly robot, that a solution is sought.

The crux of the assembly problem is, of course, in the fitting stage; for example, the actual fitting of a peg into its hole. So the approach that has been adopted is an extensive survey into the mechanics of the assembly problem. Limited work has been done on the conditions for jamming, misalignments, and chamfer effects in the static mode. This is continued and furthered into the dynamic domain. Modes of misalignment were modelled and the resultant contact forces and moments derived: the possibility of simple tactile feedback was investigated.

Armed with these basics various techniques of alignment were derived for the peg-hole problem. In particular, was one using simple tactile feedback and invariant planes contact. Invariant planes contact is a system whereby general misalignment is reduced to a planar problem through the contacting of two invariant plane surfaces.

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GLOSSARY

SOME NOTATIONS OF FREQUENT OCCURRENCE

d_p	peg diameter
D_h	hole diameter
r	peg radius
R	hole radius
C_x	peg radius, $= r$; half block width
C_y	half peg (block) length
C_r	radial clearance
C_d	diametrical clearance
ϕ_p	peg chamfer angle
ϕ_h	hole chamfer angle
μ	coefficient of friction
α_f	cone of friction semi-angle, $= \tan^{-1}(\mu)$
P	applied force
P_y	component of P in contact normal direction
P_x	component of P tangental to contact normal direction
G	gravity force, $= mg$
W	hole aligned assembly effort
R	resultant contact reaction
ξ	angle between the peg and hole axes
ψ	angle between the peg axis and the contact normal direction

CHAPTER ONE

INTRODUCTION

A number of factors make the present favourable for investigating the possibility of flexible automation; these are recent dramatic increases in labour costs, growing discontent with 'soul-destroying' jobs, and the timely advent of the inexpensive mini-computer.

To see the negative factors in proper perspective a step must be taken back in time, to 200 years ago, to the Industrial Revolution, when the West embarked on its pursuit of material wealth. The central theme of the Industrial Revolution must be the concept of 'division of labour'; it increased industrial productivity many folds, but the price it asked was the alienation of the producer from his product.

In the beginning the work of production, though divided and trivialised, was still undertaken by human labour; then, as technology grew, mechanisation began to take over more and more of the simpler tasks. The pace of mechanisation steadily increased, quickened by the demands of the two World Wars, until today when the bulk of the human contribution to secondary production is reduced to one of control only. Of course, as Science and Technology grew it also spread to embrace the sphere of control. However, at present, the state of industrial automation - where both the muscles and the control are provided by machines - is rather limited in its application. Industrial mechanisation, unlike the flexible skills of a craftsman, requires a certain product volume to justify itself on the grounds of economic viability. Completely automatic production in the classical forms, unfortunately, requires an even higher product volume to justify its procurement costs. As a result, only the very large product volume industries have automated extensively, leaving the smaller manufacturers, who form the bulk of the secondary industries, to mechanise as far as possible and rely on human labour for the remainder of the work which is intricate and requires a good deal of sensory perception and control.

This remainder of the work consumes about 60% of the manufacturing effort, and as a result, heavily reflects any industrial ailment on the labour front. In recent times, perhaps because of a new awareness brought about by higher educational standards, labour dissatisfaction has been especially apparent. Maybe the time has come when man is no longer willing to trade mental fulfillment for material wealth, and is now looking for something to take his place on the factory floor.

Because of the complex and diverse nature of this category of work, a technological solution to the problem, unlike the classical ones (Detroit type automation), having the virtues of flexibility and economy, has to date remained elusive. Small scale assembly-weighted production, typified by that found in New Zealand industry, in particular, is feeling the pressure because, unlike the progress that has been made for piece part production, there has been no relief for control intensive work (dominated by assembly) in terms of advances in flexible automation.

The arrival of the mini-computer has given a glint of hope. These then are the initiating factors for this study into flexible automatic assembly.

Extensive work has been done aimed at giving anthropomorphic qualities to machine systems, the ultimate goal of course is versatility. Although achievements so far are impressive, the present state-of-the-art of machine intelligence is primitive compared to what is envisaged to be necessary. This foreseen robot, when it arrives, is likely to be highly anthropomorphic - it may have eyes for 'seeing', fingers for touching, and certainly a computer for 'thinking'. It will also be costly. In effect, a mechanical man to replace the biological one.

It is the view of the automation group at the University of Canterbury that an assembly system with a lower order of intelligence, supported by well-designed peripherals, will perform the assembly tasks equally well. It is in this mid-range between the extremes of a simple pick-and-place machine and a fully flexible, highly complex and costly robot, that a solution is sought.

Therefore, the resulting policy is to concentrate the research effort, initially, in an area that is felt to be at the root of the assembly problem; that is, one in which the mechanics of contact and assembly are investigated. With this investigation, various ideas for solution will be examined and tried, so hopefully an eventual solution system will emerge. These solution proposals, in keeping with the desired complexity of the sought solution, will at first be simple in concept and easy to implement, and as functional demands are increased they will correspondingly grow in sophistication, but it is believed that a mid-range solution is still attainable.

Because the problem of assembly, even when simplified by the enforcement of easing constraints, is still a difficult one, this initial phase of research (this project is in the first stage of research on this topic to be undertaken at the University of Canterbury), will therefore concentrate on pure and simplified fundamentals of the problem area. However, the essence of the problem must be present for it is hoped that the acquired knowledge will form the foundations from which following sophistication may rise. So, in this thesis, the focus of attention will be on the assembly of a cylindrical peg into a cylindrical hole.

As a result of the preceding discussion the scope and arrangement of this thesis will be in the following manner.

To begin, there is a further discussion on the historical setting, on the work that has already been done in the area of automation, and on the philosophy held by this research group.

Next, there are several chapters, grouped under the title of "Part One: Definition of the Assembly Problem". As is indicated by its title, here the assembly problem is examined; the areas investigated are seen to belong to the assembly process, or the assembly components themselves. The findings, for example, the positional constraint envelopes derived for relative component placement, are seen as being specific only to the product (peg and hole) and not to the working strategy used.

The next group of chapters, labelled "Part Two: Body Contacts and Tactile Sensing", examines the phenomonon of body contacts and contact reaction forces as felt from the peg. The analysis here was aimed at the derivation of workable correlations between peg-hole misalignments and the felt contact reactions. Also considered were various contact based assembly methods, like chamfer effects, and loose confinement manipulation of the peg.

The last grouping of chapters, Part Three: Solution Systems, uses some of the relations derived, and concepts borne of the previous section, in some solution proposals. A particular system, of invariant planes contact, was selected as the peg-hole assembly strategy, and further analysed in greater detail. Experimentation was carried out to verify the central concept behind this solution and the resulting conclusions discussed.

Finally, a general conclusion sums up the findings of this project and proffers recommendations on the direction of further research in this immediate area.

CHAPTER TWO

PHILOSOPHY

2.1 Industry and the Worker: A History

Before the Industrial Revolution nearly all of the secondary production was undertaken by craftsmen. These people were highly skilled, yet they were not specialists in the modern sense of the word, for they made complete articles. Whether blacksmiths, or potters, or carpenters, these workers were tightly organised into self-governing guilds which controlled prices, wages and production methods, defined rules of practice and fostered high ethical standards. But the Guilds had little tolerance for progress or competition. Though proud and conservative, the medieval craftsman was happy and fulfilled. Production-wise the important aspect to emphasise is that each man made complete articles - production was labour-intensive.

Then in the 18th century came the age of the machines. These were creative times. In 1776 Adam Smith in his "The Wealth of the Nations", proposed the concept of 'division of labour' whereby a job was divided into a large number of menial tasks. This trivialised the craftsman's work and downgraded labour for production activities could now be divided and assigned to lower skilled workers, children, and increasingly to machines. Not only did this 'specialisation' increase the productive efficiency of each man, but trivialised production enabled vast numbers of unskilled workers to join the production force. The death-knell of the Guilds heralded in the age of the factory, and so came about the Industrial Revolution. This concept of production, coupled with mechanisation, increased tremendously the output per man. Before the Industrial Revolution only about 10% of the people were above subsistence, supported by those that were not; nowadays between 80 - 90%

of the people in an industrialised society are materially well-off.

The two world wars brought great jumps in man's knowledge and technology and served to accelerate further mechanisation. Machines supplied more and more of the muscles and man's task was increasingly reduced to one of control.

When the Industrial Revolution was at the peak of its flux, Benjamin Disraeli, echoing the Victorian view and hope, said : "... increased means and increased leisure are the two civilisers of man". This has turned out to be a mirage. The workers freed from unremitting toil did not imitate the cultural and intellectual practices of the leisured classes of earlier periods, nor has the old socialist dream of a fresh, new, working class culture been fulfilled. Instead, life is now crammed with flash cars, T.V., outboard motors, and barbecue grills - non-stop distractions that would have been termed vulgar, if not harmful, by Disraeli.

The displacement of work has not been replaced by a corresponding increase in culture, because the attitude towards work has shifted. Work, to medieval man, was a fulfilment of life; it was set in rules of tradition, morals and custom. Then, with an 80 - 90 hour working week, if life was to have any meaning, it had to be found in the job. Today, work is regarded as an irksome chore undertaken to get more money. For the same satisfaction that was derived by the craftsman who made the complete product is not available to the 'specialist' in the production line who contributes infinitesimally to the final product by doing the same thing over and over again. As the average worker still spends a greater part of his waking hours tied to the humdrum of trivialised production, it is no wonder he spends his leisure hours in a phrenetic search for distractions!

Now with the development of sophisticated control theory and the advent of the low priced small computers, not only the muscles, but the control can, to a large extent, be 'mechanised'. Technology has advanced sufficiently to enable serious work to be done in the area of using the computer to control the performing of delicate operations that, up to the present, has demanded the use of human beings.

Thus when automation, in its full sense, arrives, man will at last shrug off his industrial yoke. In this sense, automation can be seen as the maturing stage of mechanised secondary production which had its infancy in the concepts of Adam Smith just 200 years ago. Automation will free man from the actual trivia of production, the robots taking over the mundane and repetitive, leaving man the tasks of management, research and development, and maintenance. Then the producer will be no longer alienated from his product, and so, like the medieval artisan, the future industrial man will have responsibility, interest, and pride and satisfaction in his work.

Looking at the scene with an economic slant, it would appear that the driving effort behind this change is the spiralling increase in labour costs in the past few decades thus forcing a capital-weighted bias in industry. However, a penetrating investigation into the psychology of the situation would show this to be a manifestation of basic dissatisfaction from the worker. Perhaps the general improvement of education has awakened a new awareness.

2.2 Evolution of Automation

"When looms weave by themselves, man's slavery will end". This quotation from Aristotle shows that even in ancient Greece automatic manufacturing existed, if only as a distant aspiration. There is no doubt that mankind has long been trying to build machines that will perform intricate and laborious tasks with the minimum of human help. In the area of replacing man's muscles, there is little need to elaborate on the advances that have been made. In the sphere of replacing man's guiding intelligence, however, on the whole only a little has been accomplished. Though there were glimpses of automation in the past, it is still like the proverbial iceberg floating in the sea of mechanisation. It seems, like everything else, the advent of automation is governed by the all-encompassing rules of economics as indeed was mechanisation. Elwood Buffa, writing about production processes, has this to say:

> *"The economics of industrial mechanisation logically began with the tasks where mechanisation could be justified and where machines could perform tasks that could not be accomplished manually. In the march of economic events, labour has become more expensive relative to machines and a continuous process of substitution has taken place. It is logical that the most difficult technological developments should not be the first ones applied. Even if known one hundred years ago, these ideas would not have been justified economically. Therefore, the substitution of machines to perform the control functions of the human operator had to wait until the present when labour rates are very high."*[(1)]

Indeed, one hundred years ago some of these ideas had been known. Though unfortunately full records of the historical evolution of manufacturing are scant, there exist some glimpses of the engineering genius of the past. The first glimpse goes back almost 500 years to the works of Leonardo da Vinci, which include automatic needle and file cutting machines and plans for an automatic sawmill. In the area of textile machinery there was much progress so that by the mid 19th Century these machines had reached such a high degree of automaticity that they are often cited as classic examples of mechanical inventiveness of that age. In fact, a basic concept of today's automation - punched card or tape control of machinery - was originally conceived for the early loom.

Oliver Evans is often credited with building the first "automatic" factory as far back as 1784. While by today's standard his technology may have been primitive, Evans' flour mill, which reduced labour content by "fully one half", is noteworthy for its high degree of automaticity. In his book which contains the theories and techniques for the construction of his mill, Evans describes the use of bucket elevators, screw conveyors, weigh hoppers and a primitive version of the belt conveyor.

The names of Marc Brunel and Thomas Blanchard are prominantly associated with the pioneering work on automatic parts manufacturing. Brunel in 1808 built for the British Admiralty an automatic machinery system to make ships' pulley blocks. This equipment enabled 10 men to do the work of 110. Blanchard, in 1822, performed three dimensional copy milling on his contour tracing gunstock lathe. A master shape was placed in the tracing cradle and a profiling system then controlled the cutting tools so as to produce a copy of the master from a rough block of wood.

Then the automobile came along, and in the early 1900's perhaps some of the most outstanding accomplishments in automatic forming and assembly were achieved. In the forefront was the A.O. Smith Corporation's automatic frame production line, built around the 1920's, which turned out a chassis every 8 to 10 seconds, performing 552 operations in a 1½ hr manufacturing cycle. This performance was due to the then novel concept of continuous movement through manufacturing operations. This is a fundamental and powerful manufacturing concept first introduced by Ford in the assembly of flywheel magnetos for his cars. What had previously been a 20 minute job for one man was split into 29 operations to be carried out progressively as the assembly moved down the line from man to man; labour content was reduced to 5 minutes per unit.

Through the years this continuous movement concept has undergone rapid refinement and the operation at each of the stations has become more and more mechanised. Market competition forced continual streamlining and a rapid mechanical evolution. With growth came capacity, and the result is the massive production machinery of today.

However, generally speaking, human control skills are still an essential part of the production system.

2.3 Production Automation Today

If a single word was sought to describe the nature of the productive systems of today, that word would be 'diverse'. The nature of productive systems can be likened to the demographic characteristics of natural groups of people - consisting of different races, idiosyncracies included, and within these a whole spread of different ages. But in the place of race, put the word 'specialisation', and for age, substitute 'level of technology'. As an illustration, the specialist branch might be the electronics industry with its general characteristics of precision and miniaturisation. Within this sector is found the most automatic IC production facilities and, at the same time, at the other end of the spectrum, the very labour intensive radio assembly lines.

Some industries have managed to automate, others have not. For those that have, the reasons are various; it may be due to capacity, competition, labour shortages or production costs. The very same reason that enticed one manufacturer to automate might discourage another, for each must evaluate for his own particular conditions. Indeed, each process or operation will give differing evaluations for seldom is found a factory with the same level of mechanisation, let alone automation, throughout.

In this light then, the nature of present day production automation will be examined. The general conditions for its application, the main characteristics, and the advantages and disadvantages of different systems will be compared.

It would help to clarify matters if industrial automation is seen to consist of two main branches. The first is concerned with the control of processes; that is, automatic control of an engineering system. This involves the feedback of information to maintain, to within predetermined limits, control of some variable, be it a dimension, temperature or pressure. An example of this type of automation in manufacture is the numerical control of machine tools. The second branch of automation is essentially advanced mechanisation. Feedback may or may not be involved. This branch concerns the automatic handling of parts between operations, establishing continuous movement in an automatic fashion. Automatic continuous production is usually manifested in either one of two ways: using the automatic transfer machine concept, or the multi-station indexing machine concept.

The classic transfer machine is one large unified machine designed to perform a sequence of operations. The design concept is to create one large machine base and on this to mount a series of workheads. Transfer mechanisms are employed to move the workpiece or assembly from station to station with split second timing and to precise locations. Advantages of this compact, integrated and unified piece of machinery are high productivity, rapid processing, simplified handling, reduction in space requirement, reduction of labour and the reduction of in-process inventory. Disadvantages are its complexity, expense and inflexibility. Each system is uniquely designed for a particular job.

The second class of machinery, on the other hand, is built around some transportation device - usually a conveyor or monorail, or a multi-station indexing machine. The basic principle here is to index a series of work-holding fixtures through a succession of work stations, pausing at each station simultaneously and for a constant time interval so that at each fixture/station interface a production operation is performed. So, if a particular workpiece is followed, it will be seen to undergo a designed sequence of operations, whether part-producing or assembly, as it progresses through the course of work stations until the workpiece is completed. This is an illustration of the fundamental principle behind this class of machines. There are several variations which include workheads that move with the work-piece while the operation is being carried out, the workpiece carrier moving uniformly and constantly. Another embodiment has buffers of workpieces before each workstation in an attempt to cushion the effects of a station breakdown. Flexibility is the property emphas-ised in this concept; compactness is secondary. The system is designed to perform a range of operations on a variety of parts, there being little or no integration between adjacent workheads except that all of them must complete their function in the same time interval. By simply rearranging, adding to or removing from the sequence of work-stations, any production sequence can be built up. At each station the operations can be automatic, semi-automatic or manual, but for automatic operations this concept has a significant drawback for it is difficult to maintain positional accuracy at a station after a sequence of indexing.

Basically these are the two systems of automation employed in industry at the present time. They are employed in a spread of act-ivities ranging from assembly and manufacture, to inspection and pack-aging. It would be true to say that, in general, the transfer machine with its better accuracy characteristics is used where production volume deems it economically viable. Typically this would be the automobile and its associated industries. On the other hand, the multi-station indexing machine in rejecting the notion of inflexibility has been favoured as perhaps a more general purpose tool. Thus it finds use in the lower product volume industries and in areas that are otherwise difficult or costly to automate.

A factor which must be considered is the economic viability of replacing a man with a machine even if the required technology is available to build a specialised mechanical replacement. An operation, typically one of control, may be "automatable", but the resulting mechanism for replacing a semi-skilled labourer may be so technically cumbersome, or inordinately expensive, that the venture might not be practically feasible. So, it is found that in the average production process, especially in one of assembly, the process sequence covers quite a wide span of mechanisation. Some examples are : the production of a part may be automatic, while the inspection and packaging is manual; a metal press must be hand loaded; a bearing must be aligned manually before being mechanically pressed home.

It would be wrong to give the impression that automation is widespread. Only a relatively small proportion of manufacturing is automated to the extent that production costs are significantly reduced. Whether a production process is automated depends on a host of factors, the main ones being technical and economic. To state the criteria simply: if the product is made in large quantities and the working material is reasonably predictable, as in the automotive, oil refining or electronic parts industries, or if the product is reasonably simple, as in some food processing, plants, glass or paper mills, then there is an economic incentive to automate. However, it is found that the bulk of the industries do not fall into these categories. They are concerned with products which may involve none of these factors. The product range may be diverse and the product volume small; the working material may be inconsistent and difficult to control, and/or the product might be an assembly of a large number of parts. These production characteristics would be found in the majority of the manufacturing industries throughout the world, for even the most advanced industry is usually supported on a wide base of the smaller and less progressive.

Typically then, a factory involved in secondary production may have a diverse range of products each of which is sold in small quantities. In addition, the products might all be multi-parts - the components are made from stock materials and/or brought in and assembled. A "diverse range", in "small quantities", "multi-parts", imply that with the present available schemes for automation, it is economically out of the question to go automatic. A number of complex production machines will have to be built and each of these will, in economic terms, have a break-even volume which is unacceptably high.

It is not that there is no economic compulsion to automate. For over the last decade, both the average labour costs and the price of materials have gone up enormously. The brunt of these increases has been borne by the off-setting effect of improved manufacturing efficiency almost entirely in the area of piece parts production. For it is in this area that the automatic lathes and numerical control machines with their flexibility of usage, find profitable application. In the area of assembly, however, where about 60% of the manufacturing effort is spent, there has been very little progress. It seems that because of the more complex and diverse nature of the assembly problem, solutions like those proffered for parts producing operations which are relatively inexpensive and reasonably flexible, have to the present, remained elusive.

Economically it is easy to justify, in terms of attractive short term gains, the automation of piece parts production by installing, for example, an automatic lathe or multihead indexing machine. Usually only a small area of the factory is affected. But the justification for a change of concept in assembly using the classical solution with its questions of adaptability, wholesale revision of management ideas and plant layout, and long payback period in an environment of rapid changes, is far more difficult to state. In today's shifting markets it is indeed questionable whether any capital expenditure which has not a very short payback period or a high degree of flexibility is very wise.

So the bulk of assembly processes, though highly mechanised and assisted by machines wherever possible, is still labour intensive. This is the typical production line: process workers amassed about a moving conveyor contributing simple repetitive efforts to the collective assembly mechanism. Considering production effectiveness alone, the use of human beings is ideal, for here is a supply of intelligent, adaptive components by which any assembly process can be formed. However, these "components" are also human.

Therefore, the incentive is to automate. At present the incentive is becoming increasingly strong, for labour costs are spiralling upwards and workers are brooding in dissatisfaction. These enlightened times have brought forth disenchantment.

2.4 Current Status of Flexible Automation

Flexible automation then seems to be the answer. If a machine can be given the level of intelligence that a human process worker utilises, and his flexibility and adaptability, then this machine will find a place in today's rapidly changing industrial working place. A machine of such capability is usually given the appellation 'robot'.

What progress has been made in robotics? How advanced a state-of-the-art has economics been able to support? To these questions there are as many answers as there are 'robot' manufacturers and researchers, but the real answer lies in the application of their products in industry.

As far as application is concerned, then in general, flexible automation has made no significant inroads into the industrial effort. Numerous research institutions are actively engaged in this area; many brave attempts at a universal industrial robot have been made, but industry is still expectantly awaiting a feasible machine. In the area of material handling, there has been some success with programmable manipulators, and some of the more sophisticated examples have been applied to non-precision process work. However, in the sphere of production assembly where the need is most acute, the difficult problem areas have as yet forestalled any solutions. Maybe the application and usage of the robotic manipulators will provide fertile fields to nurture the growth of this next tier.

So at the present, applied flexible automation exists almost entirely in the area of material handling. It would be beneficial to examine briefly these devices, their capabilities and applications, and see the industrial reaction.

Industry, far from being a homogeneous entity, harbours a very wide range of characteristics and conditions, these, in turn, resolving into very different economic dispositions. As a result, for certain sectors of industry, application of robotic devices was made almost as soon as the necessary technology was available. Typically, this sector is involved in the use of radio-active or hazardous chemicals. It is in this area, then, in the late 1940's, that much pioneering work was done in the field of tele-operators. These are hand/arm manipulating devices used with a human operator in a master-slave relationship, the tele-operator directly mimicking the movements of the human operator. Human intelligence and sight, from behind a window or by a closed circuit T.V. camera, is a necessary part of the feedback loop.

Gradually, as the technology grew and various factors gathered to lower robotic devices towards the threshold of economic viability, more and more industries came within reach of being able to apply these machines to their own problem areas.

At the present time there exists a host of robot-like devices used in performing repetitive and highly controlled tasks. These machines have little or no intelligence and repeatedly perform highly predictable work cycles with the aid of a memory. Minimal communication exists with the work environment and the cycle steps are performed by dead reckoning.

Almost exclusively these are transfer devices embodied as tool-carrying arms with extension, sweep, elevation and wrist action capabilities. As can be expected there exists a very wide range of these devices offering vastly differing performances in both the areas of handling capability and control. Handling capability is in terms of load, reach, speed, and positional accuracy. Control is in terms of cycle length, movements controlled by stops or the ability to have any intermediate position within the work envelope, whether movement is point-to-point or controlled over a continuous path, and whether the cycle can be interrupted at any point, for a sub-operation, or by a signal from the associated equipment.

The programs in these machines may range from a 'hard wired' system in the simpler devices, through paper tapes to the sophisticated teachable machines with their magnetic tapes or mini computer storage. In the area of programming these devices, the robot manufacturers have tried to simplify as far as possible this complicated part of running the device. The most successful effort must be the 'teachable' robot. Here, the machine is conducted through the cycle of operations manually, through a control box and the cycle path is automatically registered in the memory.

These machines are independent or 'stand alone' units which makes them a direct replacement for man in the production line. Another property that results from this concept is that units can be installed on a trial basis, singly, or perhaps in small groups, in certain more pressing areas, or departments without unduly upsetting either the working harmony already established in the factory or the company's budget. Except for a few cases, this is how these robotic devices are being applied.

Application of the bulk of these devices has been in the area of material transfer, specifically in the type of job where conditions are regarded as injurious to the human body, and to a lesser extent, the human mind. Typically, these jobs include the loading and unloading of presses and ovens, drop forges and die casting machines; servicing machine tools; conveyor line feeding and stacking and unstacking pallets. A few of the more sophisticated devices have been successfully applied in spray painting, spot welding and simple assembly operations. It will be noted that in all these applications, the work problem is consistent and predictable and occurs in a repetitve cyclic fashion. Demanded accuracy of movement is generally no more than 0.25mm.

Since about 1970 these relatively simple vanguards of flexible automation have been on the market in the major industrial nations of the world. Japan is by far the biggest robot user, employing about 1,500 units of 50 different brands. The United States is second with 200 working units from 17 different manufacturers.

Despite these impressive figures, industrial robotics is still in its embryonic stage, and on the whole, no really significant contributions have yet been made towards the total industrial work effort[2]. Apart from the very large manufacturers, like the leaders in the automotive industry, the bulk of the robotic handling devices is used on an evaluation basis.

However, as robotics is seen as perhaps the ultimate answer to the world's industrial problems, there is an air of confidence and assurance. The Japanese, the most ardent promoters of the flexible automatic machine, have established policies at governmental level, not only to disseminate robotic technology, but to entice and help the prospective user to evaluate robotic devices[3]. In a recent questionnaire to users and prospective users, several relevant points came to the fore. A large number of manufacturers, in answering the section on expected new functions, requested an assembly robot, or functions of search, etc. that were tantamount to that. So it seems as if industry is ready for an assembly robot; it is now up to Technology.

2.5 Robotic Research and this Study

In the previous sections a brief description was given of various systems of automation which are employed today. Ideal market conditions for the application of these systems were examined, together with the stimulation of a sense of awareness of the transience of those conditions today. If it was thought that a change to flexible automation was desirable for the economic wellbeing of the mass producer, then for the lesser manufacturer, who at the moment is still chained to human labour, it is indeed necessary for their survival. Under even the largest industries is a wide and supportive base of smaller manufacturers; in a small industrial state the manufacturers may all be small. The large manufacturers can combat rising labour costs by resorting to the classic systems of automation for they produce in enough capacity to render these solutions acceptable. For the smaller manufacturer, however, there is as yet very little in the way of automation to reduce the labour content.

New Zealand's industries, when judged on an economic criterion, or compared to such states overseas, fall into the small manufacturers category. In fact, it would be safe to say that quite a high proportion of the world's industry falls into this class, whether they exist in an advanced industrial state or not. This country, however, like so many other smaller states struggling to find their industrial feet, has the attendant problem of a shortage of skilled tradesmen which makes a robotic solution very attractive. If - yes, there is an if - the cost is acceptable; even within the protective national shroud, the rules of economics, though somewhat distorted, still pervade.

There is no need for this paper to laud the advantages of flexible automation, for far more eloquent treatises covering this area have been written by prominent roboticists. It would suffice to say that judiciously applied it will bring many benefits to industry.

At this point this question may be posed: "What foreseeable system is envisaged for the immediate future?" It is obvious that production assembly has the most pressing problems, for assembly work still has the highest labour content. Thus it is hoped that a solution in this area can be proffered.

Working for this cause are a number of advanced robotic projects, in various research centres throughout the world [5,6,7,8,9]. All of them are aimed at increasing the basic 'intelligence' of the robotic systems, through which the goal of versatility may be achieved. If the present direction of this work is taken to be an indication of the ultimate target, then it seems that a very anthropomorphic robot is likely to emerge.

Briefly, the main research effort seems to be directed into two general areas: one involving artificial hand-eye co-ordination problems, and the other concerning mobile robots working in a given environment. Of course, with a comprehensive robot in mind, the distinction merges into two aspects of a more general problem.

For sensing in general, vision is the main faculty used; tactile sensing is being considered, though, to a lesser extent. When a scene or the work environs is viewed optically, to the human mind, anyway, a vast amount of information is perceived. This not only allows highly complex and delicate interactive control between the eye and the hands, but the orientation of the man to his environment (all his work objects) is established. Thus lies the attraction of using vision as the principal mode of sensory input for both the ambulatory and hand/eye experiments. At the present, the mobile robots are limited to 'seeing', approaching, and performing simple work on objects in a closed space, and navigating through simple obstacle courses across a room, while the hand/eye co-ordination experiments have been aimed at the locating, picking up, and depositing, sorting and stacking of various simple geometric shapes. More advanced feats, like the simple assembly of blocks and pegs into holes have been achieved, but the assembly tolerances involved are large, or the problem is simplified by rather limiting constraints. Though work has been concentrated in the area of solving various pattern recognition and pattern representational problems for some years now, there have been no great advances; or at least the present state-of-the-art seems rather primitive in comparison to what is envisaged to be necessary.

The faculty of tactile sensing is seen to be important for guarding the interaction of the robot with the environment and for feeling the shape and nature of the work objects. Research is being performed in both the areas of detecting contact forces in the robot wrist and hand, and determining object shape by means of a matrix of sensing pads in the palm of the robot hand. The first is for use in conjunction with the vision faculty as a short range guidance method in exercises such as assembly and stacking; the second, as perhaps an alternative to vision as the primary input.

The overall achievements so far are impressive, although to the layman the robotic feats may appear trivial, or even, frivolous. These views, besides reminding man of the incredible sophistication of what he takes for granted, also serve to illustrate the great difficulties that stand before its emulation.

In view of the slow progress and the long distance to be covered before a workable solution is obtained, many queries have been raised as to the necessity of a comprehensive robot[10]. There is no <u>a priori</u> reason why an industrial robot should be anthropomorphic in character. Perhaps its industrial function can be achieved by a range of machines of lesser 'universality'. For instance, flexible assembly machines could be designed to assemble classes of products, programmable robotic arms to man spray painting stations and robotic manipulators for simple material handling jobs. Industry has, in fact, shown that there is financial incentive to do this, even if only as an interim solution before a general purpose robot arrives. This is demonstrated by the application of handling devices with a memory to replace unskilled labourers in repetitive transfer work. In the area of assembly there exists the situation in which people are employed assembling piece parts that are organised in separate bins, or even presented one at a time at separate outlets. The assembler has little strategy to consider, the physical movements are quickly learnt, and the job is soon reduced to something suitable for an automaton. Now a robot replacing a human operator here need not be presented with an unmanageably complicated situation. If the component parts are presented unmixed, or singly at various outlets, and these conditions are closely controlled, then a robot of limited intelligence would be sufficient to do the job. Such a machine certainly seems more attainable than a mechanical man. It is the shared view of the robotic research group at Canterbury that this concept of flexible automation is relevant for the immediate future.

The present state-of-the-art in robotic handling equipment possesses sufficient positioning accuracy to place assembly components in close proximity to their respective assembled positions. What is necessary is the ability to home in from this approximate state to the assembled position. Typically, for a peg assembling into a hole, the peg as placed by a handling arm, may be within, say, half a diameter in radial misalignment, and, say, up to 10° in angular misalignment. What then seems to be required is a method of sensing and correcting misalignment over this <u>short</u> range. So, in the event of a successful and inexpensive solution to this short range assembly problem being attained, then this 'intelligence' could be married to any presently available robotic arm to give it the assembly dexterity which it now lacks. This would give a workable automatic assembly solution that falls into the low complexity low cost range, which at the same time possesses sufficient flexibility to render it economic, even in the small manufacturing industries.

It also seems to the author that even in more comprehensive robotic solutions, where long range sensing, such as vision, is used, that for manipulative work, such as assembly, a short range sensing mode is still required, because generally speaking, it is difficult to find one mode of sensing that is eminently suitable to both the long and short range extremes.

However, whatever bias is adopted on the question of strategy on the general assembly automation problem, short range sensing and manipulation will be a common problem area. This, then, is the concern of this study.

It seems logical that a study of this nature should first begin with a close examination of the problem area. To relate, with a view to the final objective, the effects and influences of the components of assembly themselves, and yield a precise and quantitative definition of the problem to be solved. This prerequisite examination of the problem is Part I of this thesis.

When the problem regions have been defined the next step, the bridge to a solution, must be built. This bridge, of course, is the method of operation of the operator or solution system, the essence of which - the mode of sensing - will be the content of Part II.

In Part III various solutions systems will be examined.

P A R T   O N E

DEFINITION OF THE PROBLEM

INTRODUCTION TO PART ONE

This section is devoted to the definition of the problems of assembly.

Logically, work on solving the problems of flexible automatic assembly must begin with an examination of the assembly operation. Different phases of the operation will present differing problems (as demanded by the particular workpieces involved), each with their particular slants and difficulties. Certain aspects of these demands will be relevant in regard to the operator, or the envisaged assembly system.

Therefore, in order that a solution can be finally attained, the relevant demands arising from these workpieces must be met. This section then is concerned with, firstly identifying, and secondly elucidating, these demands.

CHAPTER THREE

THE ASSEMBLY OPERATION

3.1 Introduction

The aim is to achieve assembly of component parts. A little thought will reveal that this simply stated objective is,in depth, quite formidable. It is a task that is only matched by the equally formidable intelligence and dexterity of man. To the machine the task presents numerous hurdles over which even the latest thinking is struggling. Even if easing constraints are enforced and the task is simplified to a level that is just acceptable within the bounds of practicality, the solving strategies are not within immediate reach.

Therefore, the initial analysis will have to be a pure and simplified one; yet it must contain the essence of the problem. Knowledge gained and familiarity acquired will thus serve as foundations on which higher structures may be built, and hopefully, successive iterations will eventually narrow the gap between what does happen and what theory can predict.

If assembly is the objective, then it seems logical that the first area to which attention is focussed should be the assembled item. A detailed examination of the characteristics of geometric forms in such an inter-relationship may yield secrets which may prove useful for achieving such a state.

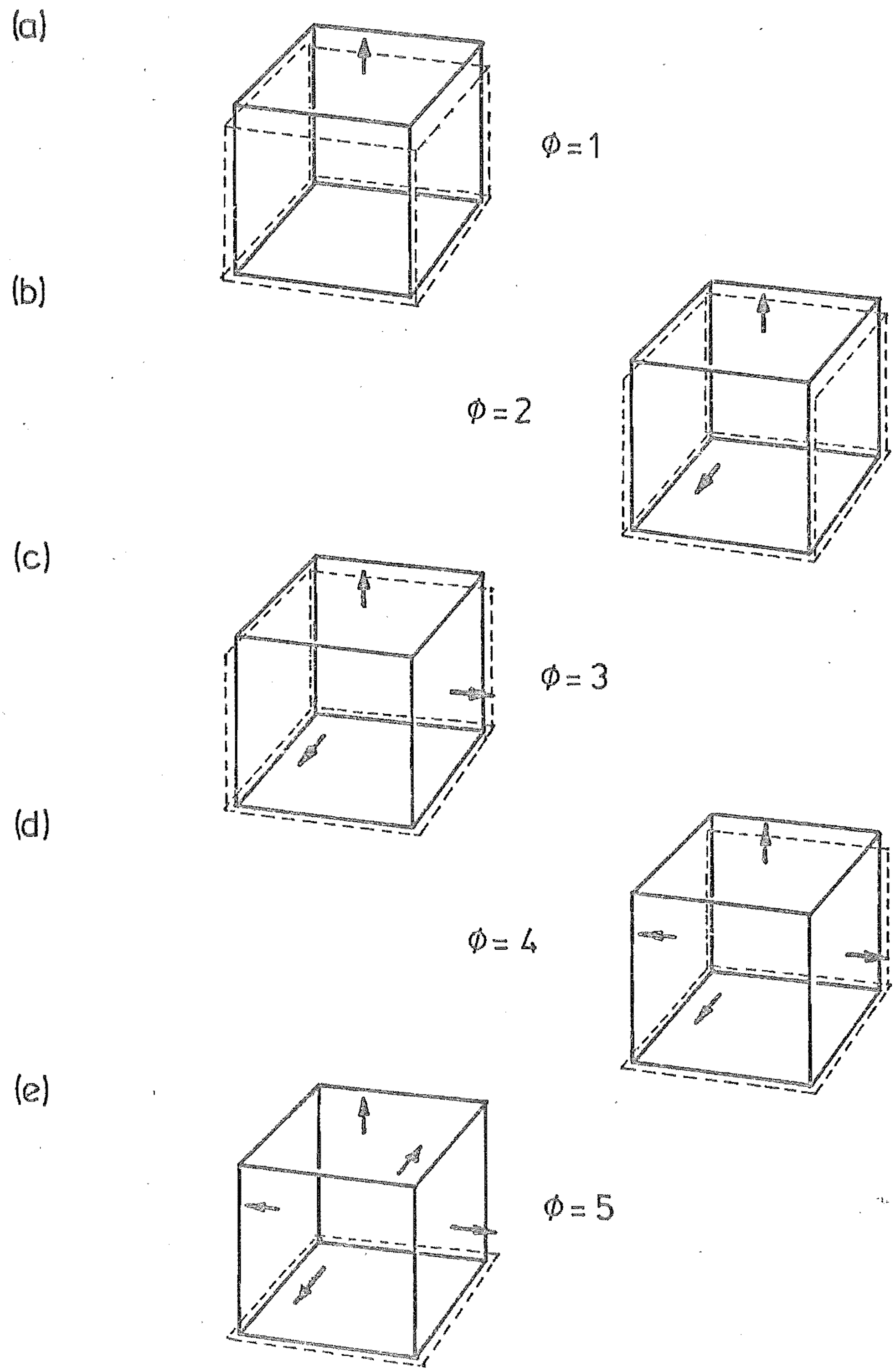
With such target characteristics clear, the study can then expand to embrace the wider concept of the whole assembly operation which will also make operational demands. In this fashion the problem areas can be located and defined.

FIG.3.1 SIMPLE CUBE AND MATING GEOMETRIES WITH ASSOCIATED TRANSLATIONAL DEGREES OF FREEDOM

ϕ = degrees of freedom

—— cube outline

---- hole outline



3.2 Assembled State Properties

The assembly of component parts is more than usually a reversible process. Thus, if an examined component in the assembled state is found to possess a certain number of degrees of freedom, then it is likely that one of these same available movements was used to effect the assembly. As an illustration, a peg in a tight fitting hole has one degree of translational freedom; that is, along the common axis of both. This degree of freedom also represents the singular direction in which movement will effect assembly from the unassembled state.

Various assemblies have a differing number of degrees of freedom depending on the mating geometry and shape. The available degrees of freedom in the assembled state correlate directly to the number of ways the components can be put together. This bears direct significance on the constraints to, and therefore the ease of, the assembly operation. This is shown by the precise and singular fashion that a threaded member has to be inserted, compared to the ways a cube may be placed onto a trace on a flat plane.

For a simple cube, there is a range of mating geometries shown in Fig. 3.1. They are illustrated in order of descending confinement starting with the cubic recess in Figure 3.1(a) to the two dimensional trace of Figure 3.1(e). If the interface geometry was axisymmetrical, say, cylindrical, there would be an additional degree of rotational freedom for each case. Also note in passing that for Figure 3.1(e), there is an additional rotational degree of freedom about the trace plane normal axis.

A study of the diagrams in Figure 3.1 will also reveal that the number of available approach directions by the free cube to its assembled position is a direct function of its degree of confinement. That is to say, the range of available assembly strategies applicable to a particular situation is governed by the degrees of freedom of that assembled state.

To assemble the block into its cubic cavity in case (a) of Figure 3.1 there is only one macroscopic orientation and direction of movement which will result in successful entry; in contrast to case (e), acceptable block orientations and closing movements are unlimited and numerous corrective movements are allowed right up to the final placement.

Now that the target area has been scrutinised, the next region to examine is the whole assembly operation before any constraints can be defined for the projected operator.

3.3 Gross Assembly Operation

At this stage it has become necessary to clarify the meaning of some words as used in this thesis. An 'assembly' is used as the noun referring to the completed, or partially completed, aggregate of component parts. The process of aggregating these parts is called the 'assembly operation'. By 'fitting' is meant the conscious manipulative process used to home a part into its planned position.

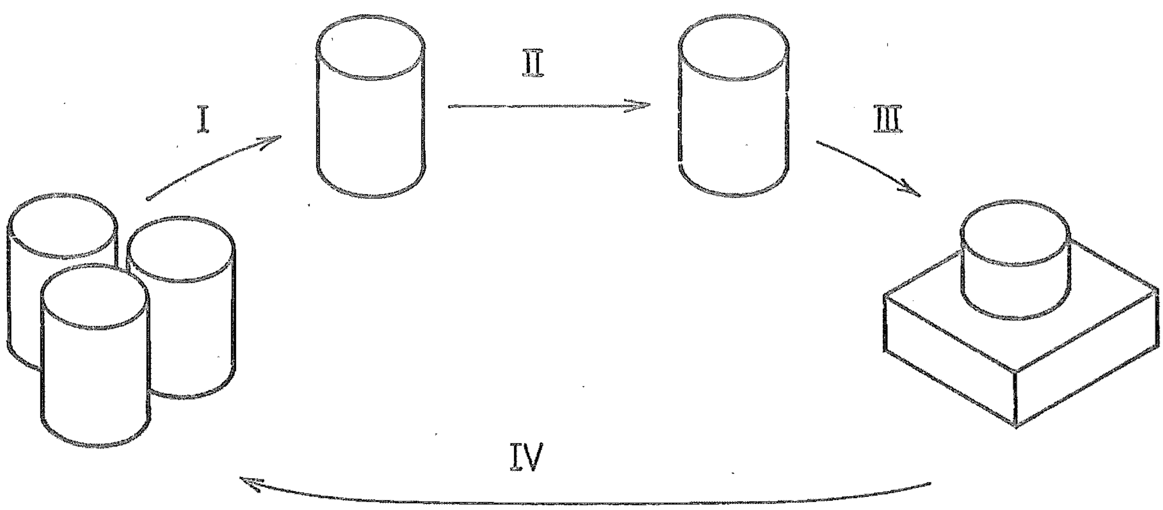
Everyone is familiar with the content of an assembly operation. Physically the process appears as a cyclic sequence of bringing together component parts to form an ordered whole in accordance with some predetermined plan. Mental involvement on behalf of the operator, after the operation sequence has been learnt, is relatively low - consisting almost entirely of memorising and carrying out that sequence of actions, interspersed with moments of higher awareness when the parts are being fitted.

For the purposes of analysis the assembly operation may be viewed as consisting of four types of activity, Figure 3.2 :

(a) Pick-up: the finding and pick-up of the component part;

(b) Carry: the transport of the component part from the bin or

FIG.3.2 PHASES OF AN OPERATIONAL STEP



Phases of an Operational Step

I : Pick-up

II : Carry

III : Placement

IV : Return

feeder, to a position near its final destination in the assembly;

(c) Placement: the placing or fitting of the component part into the planned position in the assembly geometry;

(d) Return: the repositioning of the operator manipulator in readiness for the next operation.

These four activities should be viewed as the phases of an operational step, so that the assembly operation consists of a number of these operational steps. The number of 'steps' is related to the number of operations required, this being a function of the number of component parts.

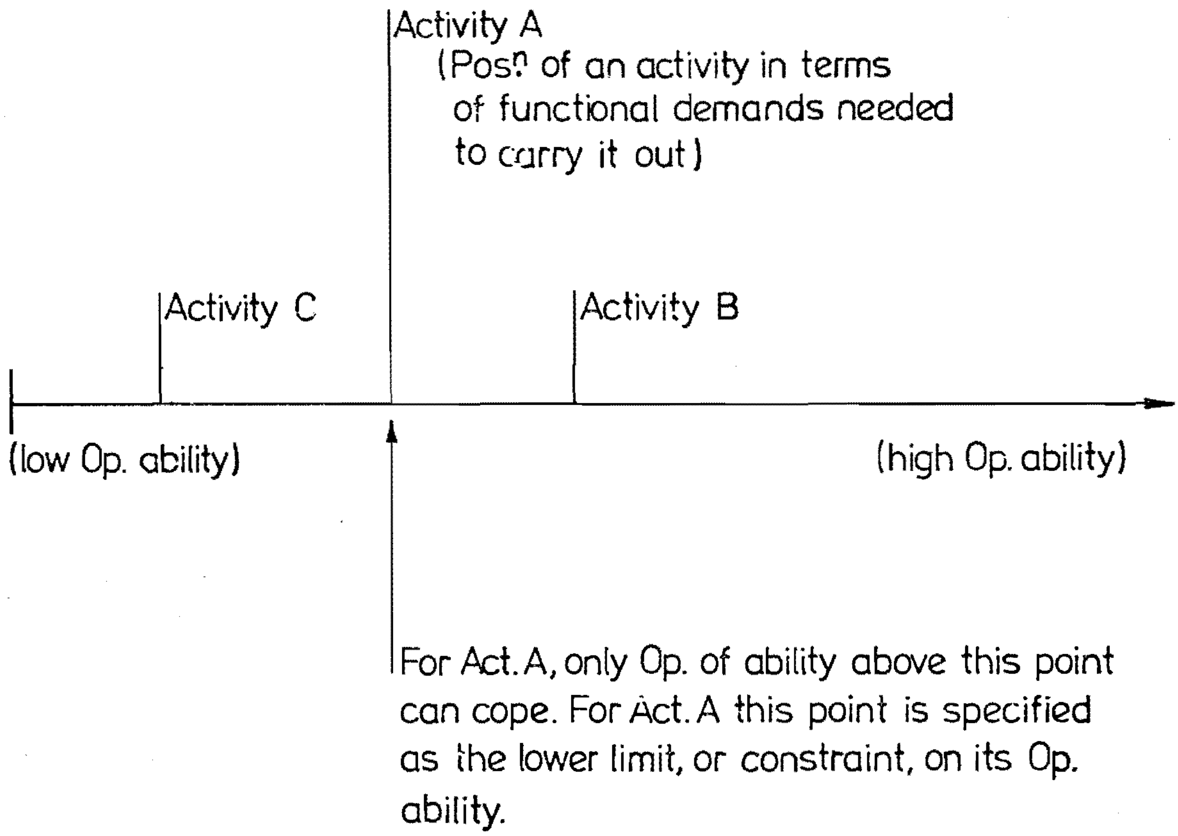
Of course, the above activities are not confined to assembly components alone, but may apply to anything else that is involved in the assembly process.

3.4 Operator Constraints

So that the phases of an operational step can be viewed in the proper context, consideration must now be given to the assembly operator.

The conception of the assembly operator, at this stage, is in terms of its functions. The functions are those dictated by the assembly procedure, modified by the strategy and the physical workpieces involved. Each activity of the assembly operational step will make functional demands on the operator. Now, these demands can be expressed as 'constraints' on a prospective operator. Constraints used in this context, define the lower limits of operator ability necessary to perform these required functions. If an activity requires functions in which the operator constraints are closely defined then the operator ability - expressed as a combination of intelligence and manipulative dexterity - must at least be above this lower limit or threshhold. In other words, an activity that makes low functional demands on an operator; that is, one that has a low constraint on the prospective operator,

FIG. 3.3 OPERATOR CONSTRAINTS



Operator constraint for activities B > A > C is an activity that can be undertaken by a wide range of operators (of a wide range of abilities). On the other hand, an activity that makes high functional demands, that is, one that has high, or rigid, operator constraints, can be undertaken only by a smaller range of operators, namely, only by those of high ability (whether ability be positioning accuracy, or manipulative skill.)

On the level of physical positioning, an activity that demands a function with a high operator constraint implies the need for high positional accuracy, that is, for tight constraints on positioning (by the operator).

Each assembly activity demands various functions of an operator, and each function is qualified by a measure of ability required to perform it, and this measure of ability is expressed as a constraint on the range of operators able to cope with the problem. (See Figure 3.3). It is the constraints for these functions, and thus the quality or amount of control needed to carry forth these functions that is of interest here. However, it would help to see the operator in its most probable form as an aid to visualising the performance of these functions. Therefore, it is envisaged that the operator will consist of a manipulator in the form of a robot arm and hand, and a computer to provide the memory and the 'intelligence'.

The manipulator would be required to possess the following physical abilities :

(a) to pick up and hold a part; i.e. to grasp;
(b) to transport the part, or itself, from one position to another;
(c) to orientate the part, relative to some co-ordinate system, on command.

As is obvious, these physical abilities enable the aforementioned operational step activities to be carried out.

Now, considering the four phases of the operational step again, it is desired to find out what constraints are demanded by these of the operator such that successful assembly can be achieved. It must be borne in mind that the four phases merge into one operational step and, as such, each is a part of a system; they are interdependent.

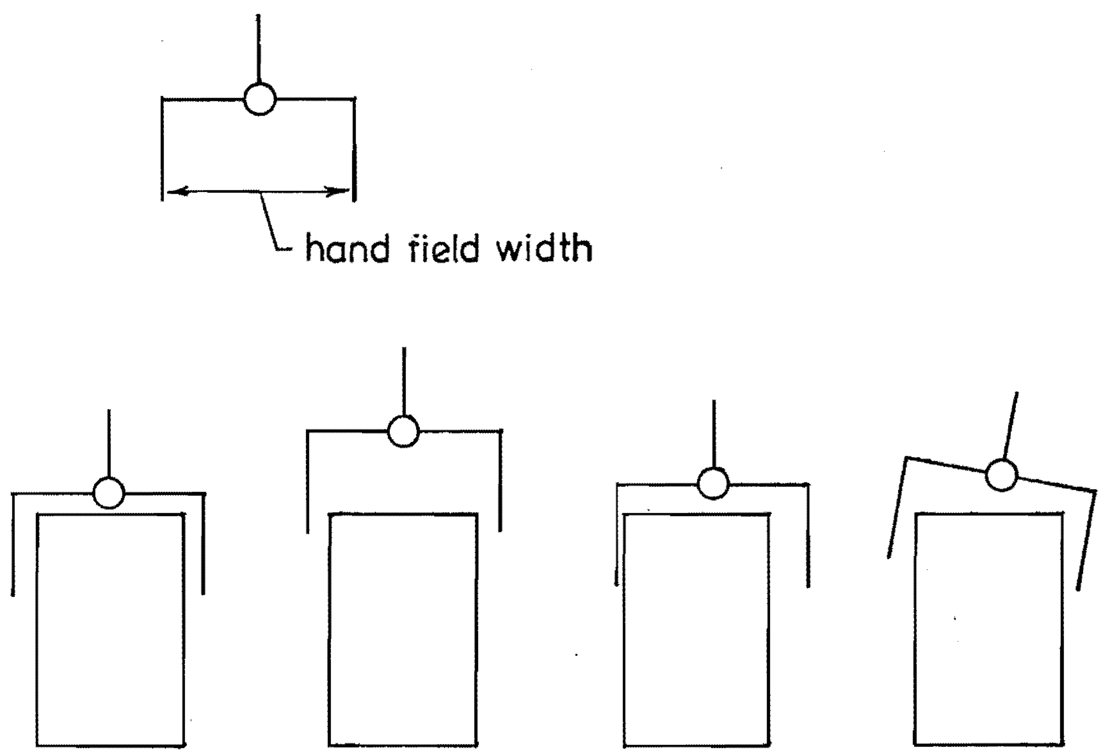
In such an operational system in which a part is picked up, carried to, and fitted into an assembly, it will be found that the accuracy constraints placed on movements at various stages of the operation is a function of design. That is the tool design, the process strategy, and the product (parts) design. Some of these factors will gather in certain areas to force very rigid constraints while elsewhere control may be less critical.

It will be found that if an activity requires a function that involves the interaction of both a component of the operator system and the workpiece then, in general, wise design of the operator system will enable the resultant constraints on the operator to be low. (This assumes that the workpiece, in this case, the components to be assembled, cannot be grossly modified in detriment to the product function). On the other hand, if a function involves the interaction of two components which both belong to the product, then no gross modifications can be made to mollify the operator constraints. With this in mind, the operator constraints for the four activities in the assembly operation step will be looked at in detail.

(1) Pick-up

If an assembly comprises of component parts that are in the same order of size, then it should not be difficult to select, judiciously, a single robot hand that will be effective on all the components to be handled. Such a hand then, designed with a generous 'field width' would allow a certain latitude in manipulator/hand positioning, see Figure 3.4.

FIG. 3.4 HAND FIELD WIDTH AND MANIPULATOR POSITIONING LATITUDE



So here the constraint on the operator can be low, and this condition is related to the hand design and how the macro-movements are achieved. Granted that a hand is wisely chosen, if the large assembly movement is performed by 'dead reckoning', i.e. through a programmed memory, then at this point the demanded accuracy of the arm motion is low. Low is a relative term, the relation is with the standard assembly type of precision. If an optical method is used for large movement navigation, then similarly, either a low visual resolution or a low accuracy arm is equally acceptable.

This illustrates the use of the term constraint if the accuracy of control demanded by the activity (of the operator) is low, by virtue of good design, then the constraint on the operator is said to be low. Conversely, the operator constraint is said to be high if the operation demands highly precise and intricate control.

(2) Carry

The only positional constraint here is that the position of termination of this carry stage is close enough to the final assembled position to be within the range of the mechanism for implementing the placement. Again the constraint on the operator can be low, for it is entirely dependent on the receiving range of the placement mechanism, or placement control.

(3) Placement

Whereas in the previous two activities good systems design could lower the constraint for accuracy of the operator, in this third activity of placement, the constraints originate from the assembly item itself. That is, the control demanded of the operator is a function of product design. Compared to the pick-up and carry activities, the constraints for the placement stage can be very rigid; in other words, the tolerance for mispositioning can be extremely small.

FIG.3.5 MACROSCOPIC DEGREES OF FREEDOM OF AN ASSEMBLED CUBE

—— cube outline
---- hole outline

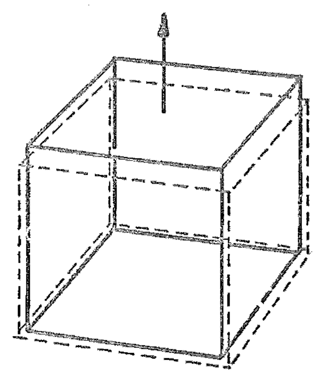
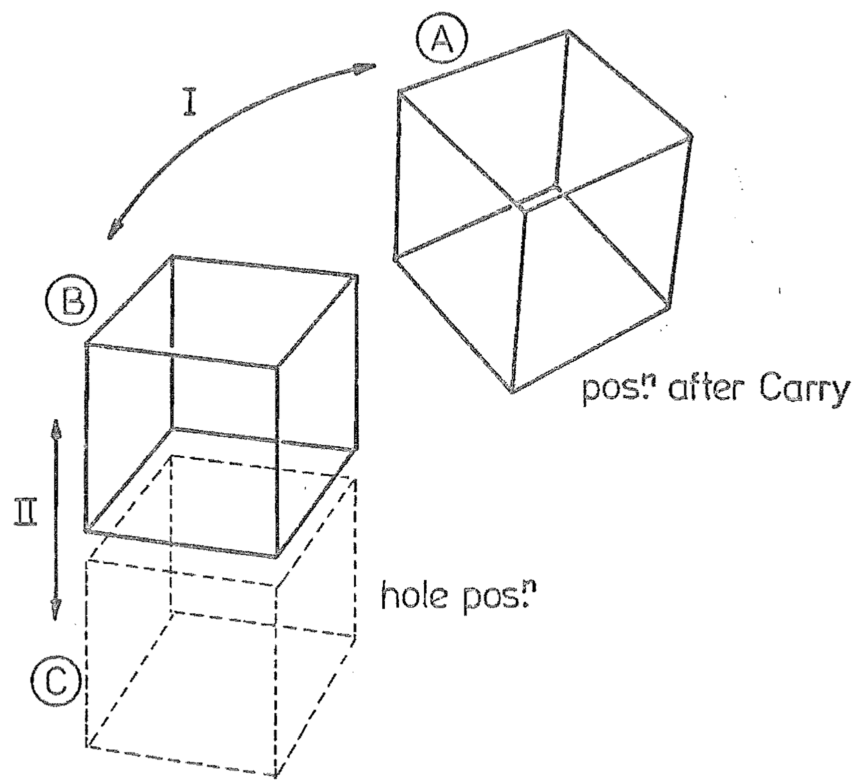


FIG.3.6 THE PLACEMENT STAGE



I : Placement Phase I   A ⟶ B
II : Placement Phase II   B ⟶ C

The properties of assembled components have already been examined in the previous section. However, it would be advantageous to review these again in the light of operator constraints.

The assembly of the cube into a close fitting cubic cavity will be used as an illustrative example, for besides being one of the most demanding placement exercises, it also occurs frequently in actual practice. A cube in its assembled position has only one macroscopic degree of freedom, that is, out of the cavity, along the axis of the hole (see Figure 3.5). Now, to effect assembly, the final movement of any manipulation must necessarily be the reverse of this singular disassembly movement, Figure 3.6.

For clarity the placement stage is sub-divided into two phases. The action of manipulating the cube, from the terminal position of the carry stage, to a position in which the cube is aligned for entry, A $\rightarrow$ B, is called Phase I. The actual act of assembly, from this aligned position, to the final placement is, B $\rightarrow$ C, Phase II. Of course, Phase II consists of moving the block, in this case, along its assembled singular degree of freedom direction. In addition, the effort direction must be parallel to this to minimise jamming.

It should be apparent that the problem of assembly lies almost entirely in the area that is now designated placement Phase I. For the following Phase II to be successful the block must be lined up within the clearance between the cube and its hole. Ideal clearance between these may be in the order of 0.2 - 0.5mm, but this is reduced by any out-of-squareness of either, by burrs, and other manufacturing defects. So, the actual tolerance for misalignment is extremely small. This then is the main difficulty of Phase I. In addition to this, the cube has to be manipulated - translated and rotated from its deposited position and orientation, to this aligned mode. This is a feat requiring a high awareness of the state of misalignment, an intelligent strategy for its solution, and physical dexterity and accuracy for its execution.

Thus, the operator constraint for placement is very rigid; a high degree of control is demanded for success.

(4) Return

This merely involves the return of the manipulator from the assembly area to the succeeding position in anticipation of the next pick-up. The constraint on the operator here is similar to that for the pick-up stage.

Now that the constraints from each activity on the operator are clearly defined, thought can be returned to the other functions that are required of the operator.

In addition to the work functions other requirements are demanded by economic and environmental factors. Some of these are cost factors, insensitivity to a factory surrounding, and a working speed that is at least comparable to man's. As can be expected, some of these functions are conflicting. For example: a highly sophisticated operator capable of meeting the constraints set above will also be very expensive; or sufficient rigidity of operator manipulators to transmit close control creates inertia problems at desired speeds.

The evaluation of the importance of the various functions, and thus how they are weighted, or even considered, is a personal matter. The subjectiveness of the appraisal is well reflected by the numerous strategies that are being offered as a solution to the same problem.

However, at this stage the main concern is assembly. Accordingly, greater emphasis must be put on the realisation of the operational functions - on the creation of a strategy for a workable assembly machine.

For if workable strategies can be conceived, then perhaps it is an easy matter to marry them to different systems to suit any particular demand.

Placement, Phase I is the stumbling block to easy automation. Obviously then this is the area on which attention should be focussed.

So, first of all, before any work is done on the implementation of Phase I, Phase II must be examined to see how it affects Phase I. In other words, Phase II follows directly after Phase I; therefore, they must be matched. If the geometrical relationship between the assembly components demands that the disposition of the element, before Phase II, is in a particular manner for success of Phase II, then Phase I must deliver the element in such a disposition.

In the next chapter the aim of the work is to relate this disposition to the assembly (peg and hole) properties.

CHAPTER FOUR

MISALIGNMENT & CLEARANCE

4.1 Introduction

In the detailed examination of the problem areas of assembly it was revealed that the most difficult part of the process is the alignment of the part so that it can be assembled. This is placement Phase I. This alignment, so that Phase II can be successful, is difficult because the tolerances to misalignments are very small, requiring a high degree of awareness and manipulative control on behalf of the operator.

But before work can be directed at achieving a solution to Phase I, which is the crux of the assembly problem, the manner in which Phase II, and ultimately, the assembly components themselves, affects the preceding Phase I, must be first investigated. Phase I precedes Phase II; Phase II is dependent on the assembly components' properties - this is the sequence. So, in order to determine the delivery specifications of Phase I, and to see how it is related to the assembly components' relative geometry, a detailed study must be made of placement Phase II.

This leads to an investigation of misalignments and how they are related to clearances. But before this is possible, many concepts and ideas, as used here, will have to be defined and expressed.

In addition, the question of whether clearance alone is sufficient to cope with operational inaccuracies, thus supplanting the Phase I search, is examined.

FIG. 4.1 RADIAL MISALIGNMENT

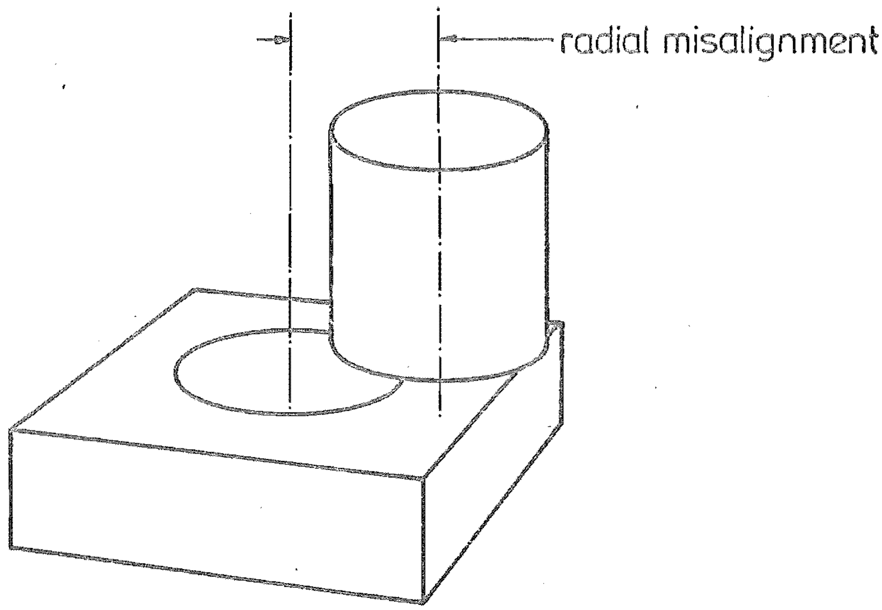


FIG. 4.2 ANGULAR MISALIGNMENT

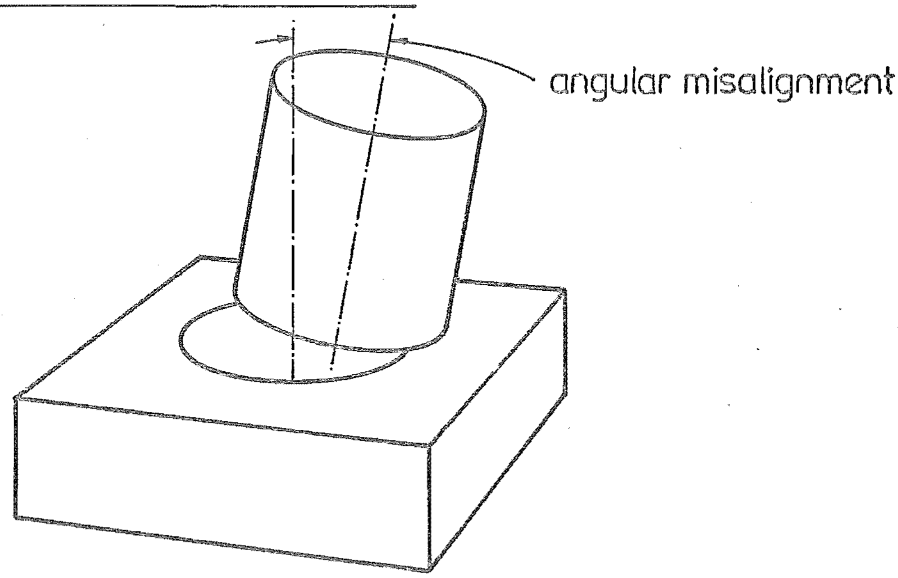
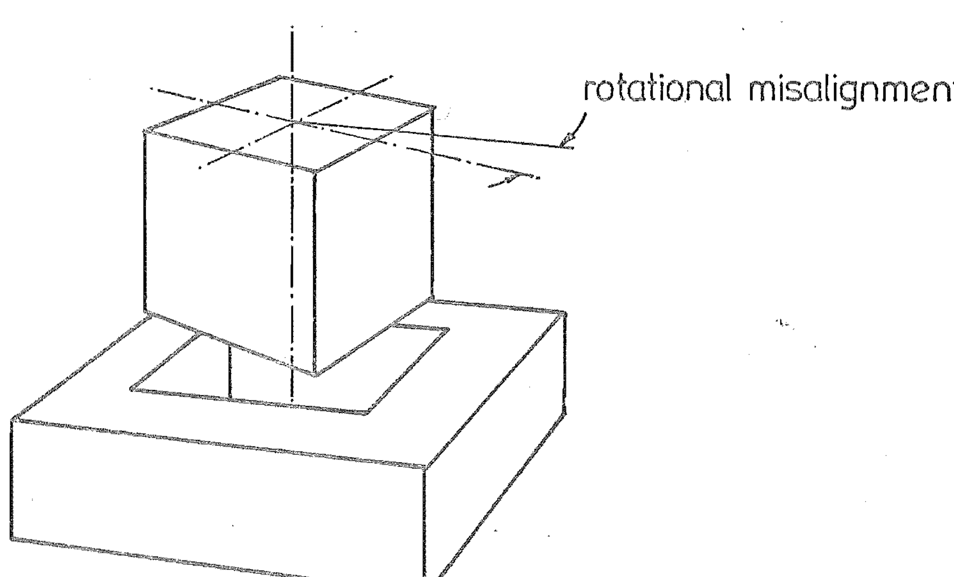


FIG. 4.3 ROTATIONAL MISALIGNMENT



4.2 Misalignment

Misalignment can take several forms.

For a symmetrical assembly, like a cylindrical peg and hole, there is radial and angular misalignment. Radial misalignment occurs when the axes of both components are parallel but are not colinear, see Figure 4.1. Angular misalignment is a state in which the axes of the components are non-parallel, see Figure 4.2. Of course, the axes that are compared are the mating ones; that is, the longitudinal axes, for the case of the peg and hole.

For a non-axisymmetrical assembly, like a rectangular sectioned peg, there is an additional degree of misalignment - one of rotation where the cross-sectional geometry is not matched- see Figure 4.3.

These are the three pure misalignment states. A case of misalignment may exhibit one, two, or all three forms.

Now that the states of misalignment have been described in general terms, a more rigorous treatment will be given to the phenomenon.

Misalignment is a relative term, describing the non-conformity of one state with a reference state. Thus a reference state to which a peg must align is implied. The state functions that are involved are geometric distance and orientation. For the case of a peg assembling into its mating hole, it was seen in the previous chapter, that the last place at which aligning can be performed is during placement Phase I; that is, immediately before the aligned peg is pushed home. The ultimate alignment is carried out here; so this is where the alignment reference co-ordinate system is required. Alignment in more precise terms describes the process of superimposing the local co-ordinate axes of the peg onto the co-ordinate axes of the reference system, see Figure 4.4.

FIG. 4.4 MISALIGNMENT

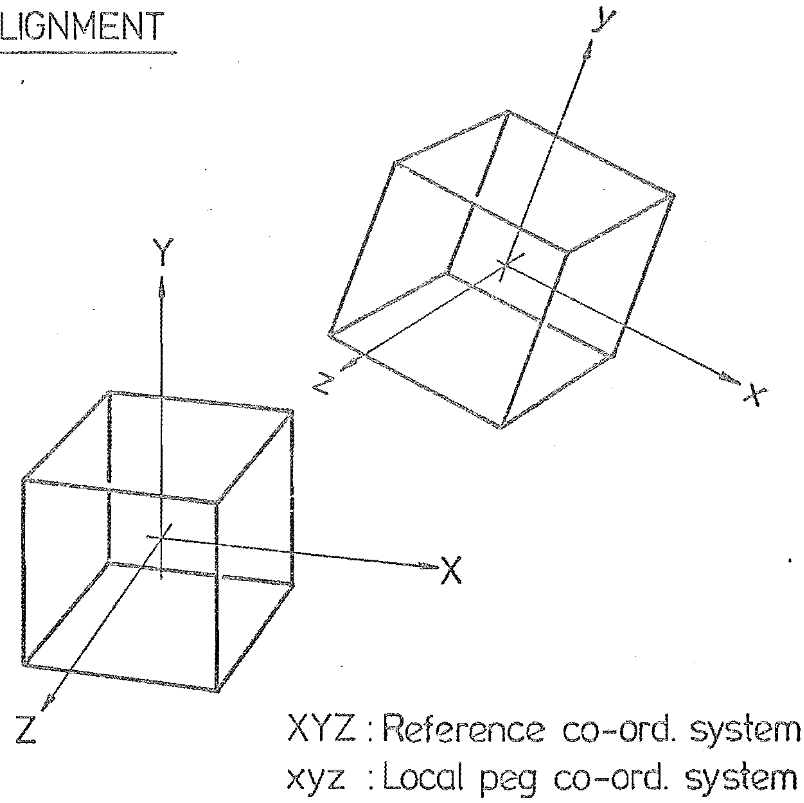
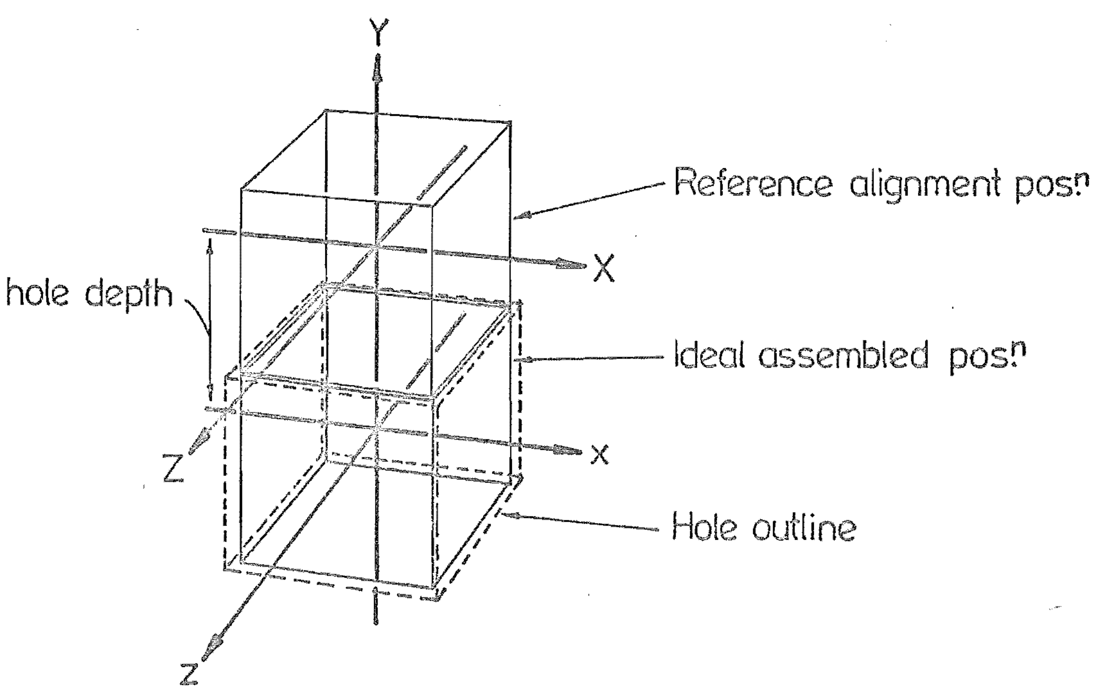


FIG. 4.5 POSITION OF ALIGNMENT CO-ORDINATE SYSTEM



The position of the reference co-ordinates is related to the hole position in the following manner. It is, in fact, the local co-ordinate system of the ideally assembled peg displaced along the hole axis, out of the hole, by a distance equal to the depth of the hole, see Figure 4.5. This then places a peg, which is perfectly aligned to the reference co-ordinates, directly aligned to and just above the hole.

Misalignment of the peg from its local reference position can be quantitatively defined by a displacement vector and two rotational directions.

If there is clearance between the peg and the hole, perfect match of the peg's local and the reference co-ordinate systems is not necessary; some latitude for misalignment is available.

Predictably, the next questions are: "How much latitude?" and "How is it related to a given clearance?" The answers to these questions must be preceded by a study of the criteria for successful assembly.

4.3 Criteria for Assembly

The preceding section described the relative position in which the male component of an assembly should be placed to achieve entry. It was also stated that a certain latitude to alignment with this position is allowed due to the fact that clearance exists between the assembly members. How much latitude is acceptable depends on the clearance available, the assembly method used and on the sophistication of the assembler intelligence.

A prerequisite is an examination of the conditions for peg entry. For a peg to enter its hole successfully a preliminary condition must be satisfied. This is that the leading face of the peg passes through the hole plane and also within a perimeter defining the hole. The hole

FIG. 4.6 THE HOLE PLANE

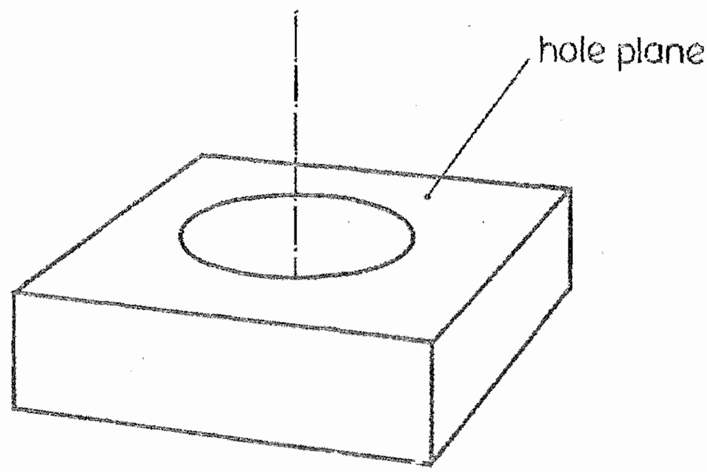
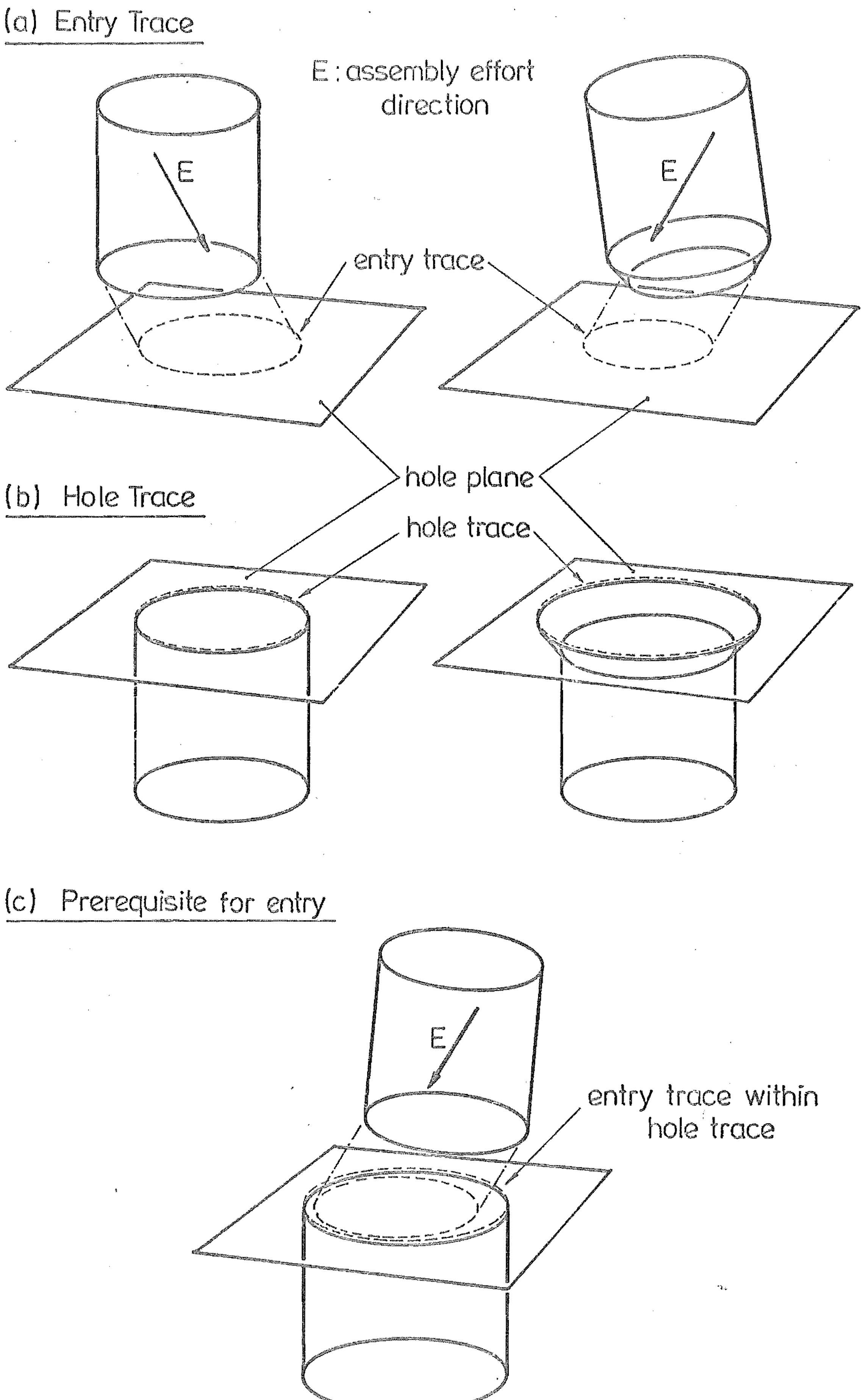


FIG. 4.7 PRIMARY PREREQUISITE FOR ENTRY



plane is defined as the surface into which the hole is bored; in practice, it is usually a plane whose normal is parallel to the hole axis. See Figure 4.6. After the entry of the peg's leading face into the hole, whether complete assembly follows or not, depends on other factors, including the direction of the assembly effort, clearance between the members, jamming, and the intelligence of the assembler.

This given prerequisite for assembly is that the leading face of the peg passes through the hole face. A better definition of this condition is that the 'entry trace' of the peg falls within the 'hole trace'. Both traces are on the hole plane. The 'entry trace' of the peg is the projection onto the hole plane of the peg's leading face in the direction of the assembly effort. The assembly effort is in the direction of the resultant force on the peg before hole contact. In general, the entry trace is elliptical; (circular special case: hole aligned effort and radial misalignment only). The hole trace is the perimeter of the effective receiving area of the hole, also projected onto the hole plane. See Figure 4.7.

Consideration of the above will show that whether an entry trace falls easily within the hole trace depends largely on the clearance between the peg and hole. Formally defined, for cylindrical components, the clearance is : radial clearance is the difference between the hole and peg radii; diametral clearance is the difference in hole and peg diameters, i.e. twice the radial clearance. Consider a case of radial misalignment of a cylindrical peg and hole - Figure 4.1. If the clearance is large then the allowable amount of radial displacement of the peg with respect to the hole and still fulfil the entry prerequisite, is also large - it can be radially displaced from its alignment reference position by an amount equal to its radial clearance. It also implies that a provision of clearance increases the latitude for positioning for cases of angular misalignment.

The reasons that sole satisfaction of the prerequisite condition does not guarantee assembly are many. If the chamfers are involved, on either the peg or the hole, then contact forces generated by their contact, may either be sympathetic or non-sympathetic to further peg entry. This, and the design of helpful chamfers, are the subjects of study in one of the following chapters. If chamfers are not involved there is still the possibility of jamming when peg and hole contact is made. Whether a preventative strategy can be adopted to combat the event of jamming, or a decisional ability can be used to determine an advantageous reaction to chamfer contact forces, depends on the present-time intelligence of the operator, or the shrewdness of the operating program.

Having defined the prerequisite condition for entry and understood its generality, attention will now be returned to the area of assembly and misalignment.

The questions to be considered are :

(a) How far can the initial (or input) misalignment to Phase II be from the reference position and the peg still be successfully assembled?

(b) What factors have an influence on this?

It will be quite obvious that operator ability has a strong influence. Operator ability can be expressed as :

(i) intelligence, or the ability to sense, and to plan a solving strategy; and

(ii) manipulative dexterity, or the possession of sufficient control over the associated physical effectors (hands, arms, etc.) to carry out that strategy.

So, an operator system of high ability will be able to cope with a less constrained problem than one with lower ability. Figures 4.8 and

FIG. 4.8 CONSTRAINT ON MISALIGNMENT

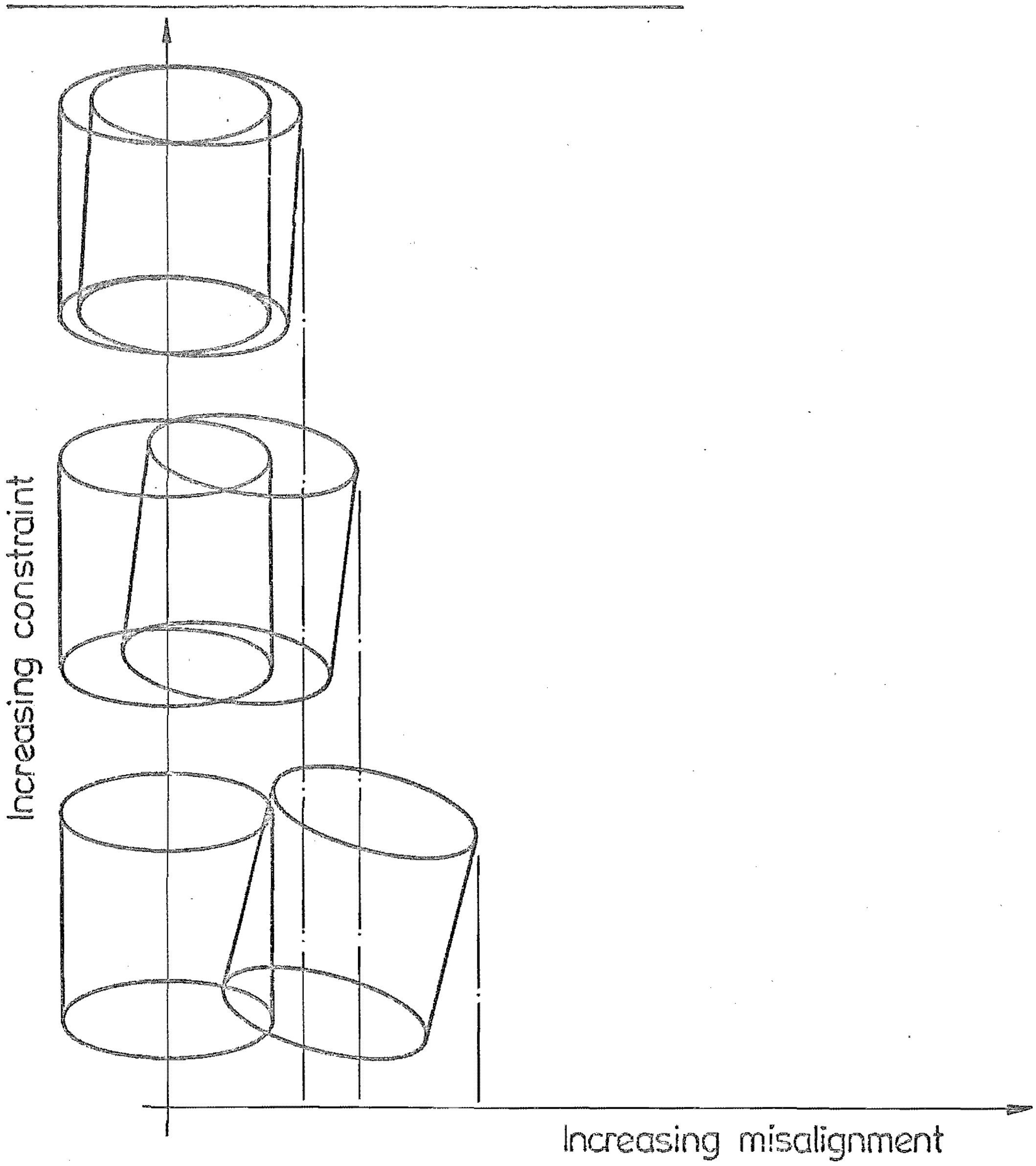
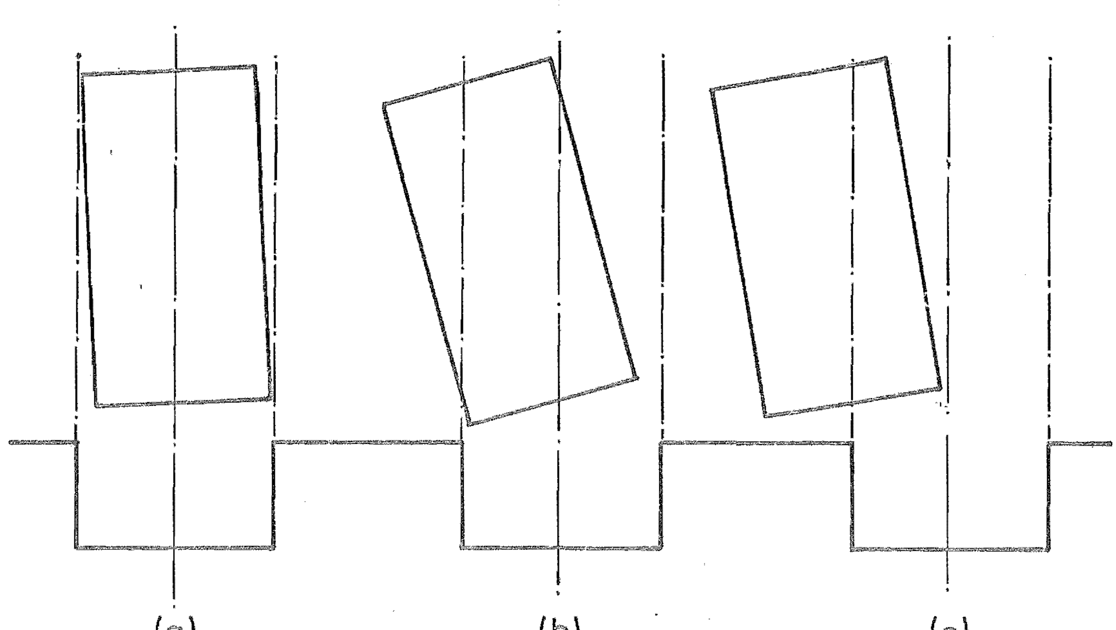


FIG. 4.9 VARIOUS MISALIGNMENTS



4.9 show the peg and hole problem with varying degrees of positional constraint - as the tolerance limit increases (the problem is less constrained), the allowable misalignment is greater.

For assembling the wide positional tolerance situation shown in Figure 4.9(c): Firstly, the misalignment (displacement and orientation) must be sensed and secondly, a strategy to eliminate these must be planned. The peg will then be manipulated according to this strategy, fulfilling the prerequisite condition for entry, and assembled. Any peg to hole wall contacts after entry could result in jamming; these would have to be reacted against favourably to prevent a jam-up. This is the performance of an operator of a high constraint limit on ability - perhaps a man.

For the low positional tolerance situation shown in Figure 4.9(a) where the peg is confined to within the cylindrical envelope projected above the hole, however, the peg merely has to be directed in a direction parallel to that of the hole axis. This is a situation where the peg is subjected to tight positional constraints, and where assembly is possible with the use of a low intelligence operator, like a placing mechanism.

In between the two extremes there are more moderate positional constraints where the tolerance limits are wider. Correspondingly, the assembly operator intelligence will be midrange, for even though sensing and strategy will be required, the difficulty of the problem is lower.

So far in this chapter the following points have been discussed :

(1) For the sake of clarity of analysis, the placement activity of the assembly step has been subdivided into the Phases I and II. Phase I is the hole search and manipulate (peg alignment) stage, and Phase II is the actual assembling (entry) stage.

(2) If Phase I is to align the peg so that in Phase II it could be directly assembled, there must exist a reference alignment position to which the peg should conform after the Phase I stage. This reference position (co-ordinate system) is then defined.

(3) The next point to be considered was, "Does the peg have to pass through this intermediate reference position exactly? Or are slight deviations allowed"? This question gave rise to the next area of consideration.

(4) How far can the peg be from this reference alignment position and still achieve entry? It was found that this depended on several factors :

    (a) The clearance between the peg and the hole;

    (b) The direction of the assembly effort;

    (c) The intelligence of the assembling operator.

    As a prerequisite for a successful entry, however, the peg trace must lie within the hole trace at the instant of entry (though this does not guarantee complete assembly). For the above factors, (a), (b) and (c), the correlation to positional deviation from the reference co-ordinates is: the greater the deviation (that is, the less constraint there is on the accuracy of Phase I), the more intelligent the operator has to be, to successfully carry out Phase II. The effect of clearance was to mollify the demand on operator intelligence.

Of course, in the limit, if the deviation from the reference co-ordinates is large, Phase II expands back to the entire placement problem. However, since the manipulation is to be performed in Phase I, the Phase II stage will be performed with little or no intelligence. Given this, the necessary tolerance level to misalignment at input to Phase II (output from Phase I), that is to the reference co-ordinates, can now be found.

Even with a no-intelligence operator, like a simple placing machine, there is allowed a certain tolerance to positional deviation from this reference position. This is due to the clearance between the peg and the hole, and the fact that a peg can be successfully assembled even if it entered with a slight angular misalignment (provided there is some flexibility in the peg manipulator). This then points to the next area of concern, namely to determine the tolerance a peg and hole has to angular misalignment upon entry, before jamming occurs. This is treated in the following chapter.

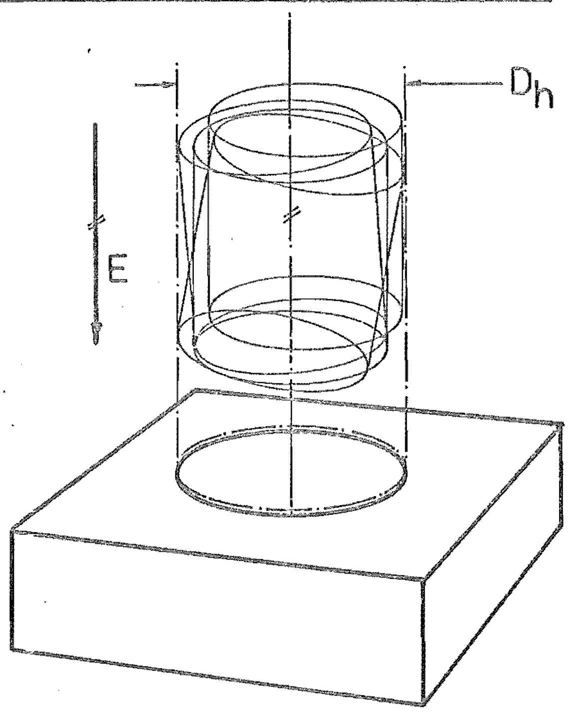
As a digression, it must be noted that there is not necessarily a change of operator (i.e. different functional qualities) in going from Phases I and II. Indeed, the same placement operator may perform both. Another case may manifest Phase I as a peg-on-plane two dimensional search, and Phase II as the drop into the assembled position when alignment is attained; this would be a two-operator placement operation.

Returning again to the subject of clearance, it will be found that in actual practice the clearance between a peg and a hole is very small, such that the tolerance to radial misalignment before entry is far smaller than that able to be achieved by available placing 'robots'. Thus needing a 'placement Phase I' mechanism to augment its ability in this particular part of the assembly operation.

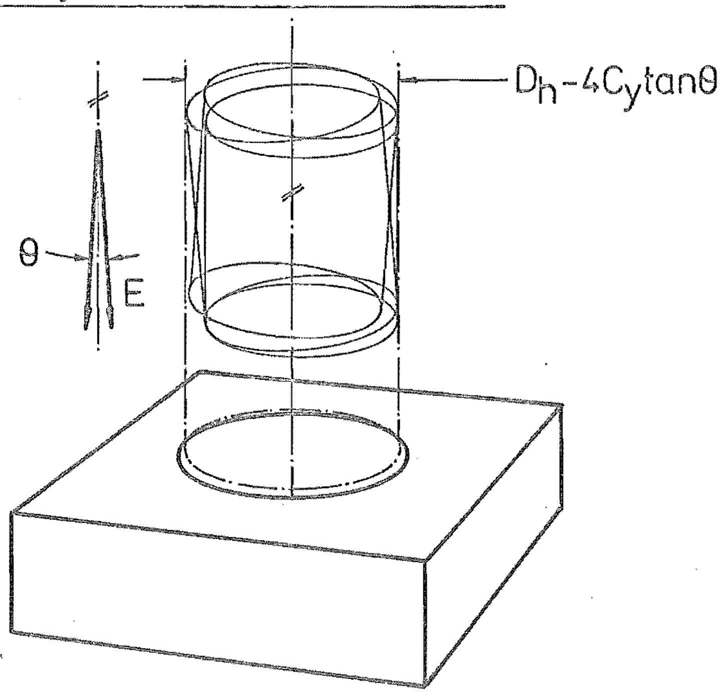
It was said that the functional abilities of the operators as demanded by the various activities, especially that of carry and placement, would be vastly different. That presently available trans-

FIG. 4.10 ALIGNMENT ENVELOPES FOR DIRECT ENTRY ASSEMBLY

(a) Assembly effort parallel to hole axis



(b) Assembly effort direction variable



E : Assembly effort vector

fer equipment could provide adequate realisation of the carry functional requirements. To show quantitatively that this equipment is not adequate to be applied also to the placement stage, thus necessitating a separate set of functional abilities for the manipulative activities of placement, the following exercise will be performed. An absence of manipulative functions implies 'direct entry assembly'. A direct entry assembly operation would operate in this manner: a holding device, either a robotic hand/arm or a more rigid embodiment of the carry functions, would pick up the peg, carry it to the hole and directly place the peg into its assembled position. Here the division of the operation into the pick-up, carry and placement activities may seem arbitrary as they are performed in a continuous sequence; however, the functions are still distinct. Even though no fitting is required, the activities of placement, Phases I and II, can still be regarded as consecutive parts of an assembly sequence performed in one movement. When the peg is momentarily in the position B, that is, between the Phases I and II, to be successfully assembled, it must lie within the narrow limits of misalignment from its alignment reference position. Assuming the direction of the assembly effort to be parallel to the hole axis, the peg must lie within a certain envelope. This cylindrical envelope is centred on the alignment reference co-ordinate axes and has a diameter, D_h, equal to that of the hole's, as shown in Figure 4.10(a). The forms that misalignment can take inside this envelope can be radial, angular or both. If the direction of the assembly effort is not parallel to the hole axis, the diameter of the alignment envelope is correspondingly reduced. Quantitatively, if the effort direction varies by up to an angle θ from the hole axis direction, then the envelope diameter is reduced from D_h to

$$D_h - 4C_y \tan \theta \qquad (4.1)$$

Where $2C_y$ is the peg length - see Figure 4.10(b).

The forms of alignment and the direction of the assembly effort, being entities in the real universe, are subject to the rules of probability. A peg cannot be placed in a definite position every time; it can only be placed in a region around that position, and the limits on the extent of that region can be specified with the corresponding probability of containing a placement. So for a direct entry assembly not only is the alignment and the direction of assembly effort subject to probability, but also the size of the alignment envelope. It is because of the probablistic nature of the functions and the elements of an assembly system that tolerance limits are an essential part of the design considerations.

As an exercise to quantify the chances of direct entry assembly, a probablistic model will be set up to calculate the probability of direct assembly, considering just one mode of misalignment - radial misalignment.

4.4 Probablistic Model of Assembly

An ideal cylindrical peg of radius, r, is to be assembled into an ideal cylindrical hole of radius R. The radial clearance, C_r, is

$$C_r = R - r \tag{4.2}$$

assuming $R > r$.

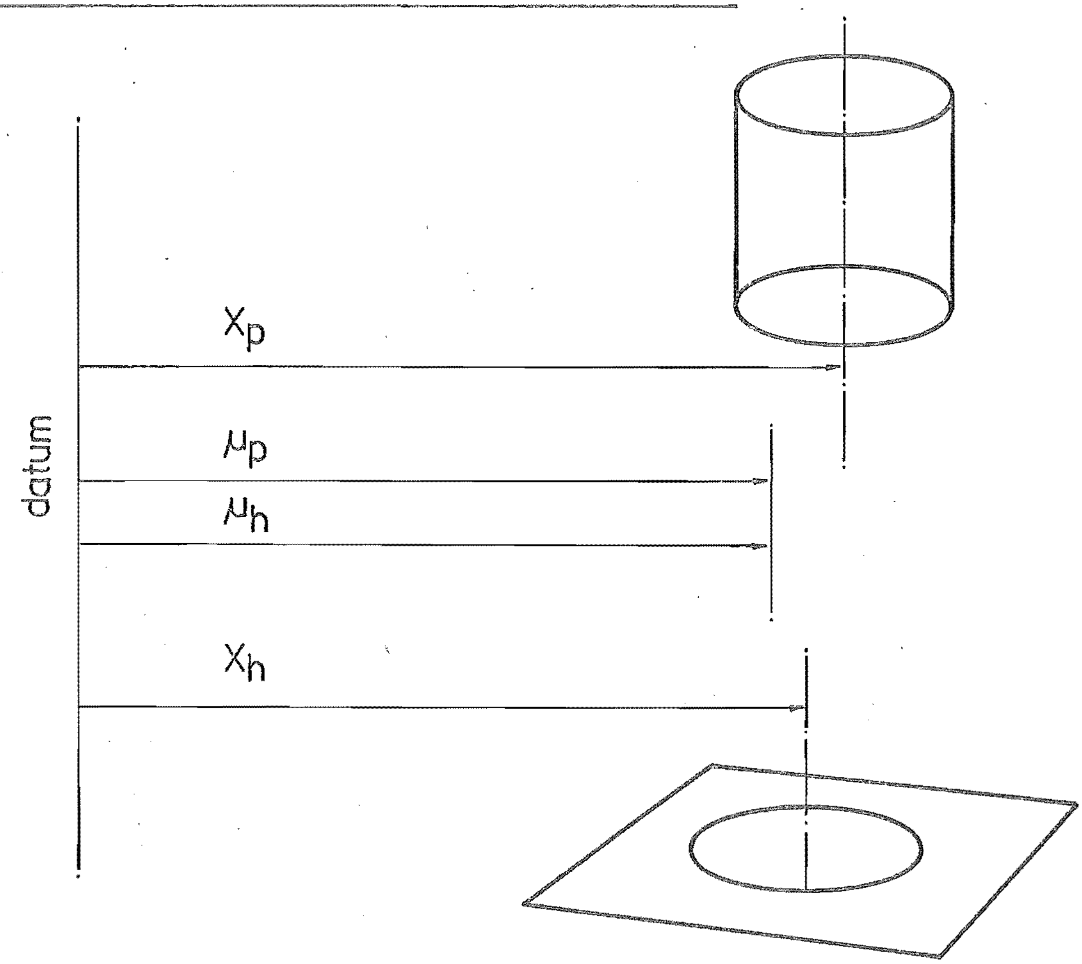
The other elements of this model are :

(i) an ideal hand/arm manipulator that will place the peg, with only radial misalignment about a mean position (referred to a datum), normally distributed;

(ii) an ideal assembly jig holding the hole subject only to radial misalignment, also normally distributed about a mean position.

Reference to Figure 4.11 will clarify the following .

FIG. 4.11 PROBABLISTIC MODEL OF ASSEMBLY



The distance between the peg centreline and the datum, X_p, is normally distributed with a standard deviation σ_p, about a desired mean position, μ_p.

The distance between the hole centreline and the datum, X_h, is normally distributed with a standard deviation, σ_h, about a desired mean position, μ_h.

Assuming no bias in the mean positions :

$$\mu_p = \mu_h \tag{4.3}$$

The peg will assemble into its hole if the difference between the distances X_h and X_p, Δ_x, is within the clearance, i.e.

$$-C_r \leqslant \Delta_x = (X_h - X_p) \leqslant C_r \tag{4.4}$$

Both the peg and the hole positions are independent random variables of normal distribution; therefore, their X, μ, and σ can be combined linearly and the resultant distribution is also normal.

What is required is the probability of $(X_h - X_p) = \Delta_x$ lying between $\pm C_r$, i.e. $P\,(-C_r \leqslant \Delta_x \leqslant C_r)$. (4.5) So Δ_x becomes the new independent random variable with a new joint mean, μ_j, and standard deviation σ_j,

$$\mu_j = \mu_h - \mu_p = 0 \qquad \text{from Equation (4.3)}$$

$$\text{and } \sigma_j = \sqrt{\sigma_p^{\,2} + \sigma_h^{\,2}} \tag{4.6}$$

converting Equation 4.5 to a standard normal distribution :

$$\left(\mathcal{S} = \frac{\Delta_x - \mu_j}{\sigma_j} \right)$$

$$\text{Probability of fitting} = P\left[\frac{-C_r}{\sigma_j} \leqslant \mathcal{S} \leqslant \frac{C_r}{\sigma_j} \right] \tag{4.7}$$

Solving Equation (4.7) for percentage confidence levels -

$$\text{For a 95\% probability of success} \quad \frac{C_r}{\sigma_j} = 1.96$$

$$\text{For a 99\% probability of success} \quad \frac{C_r}{\sigma_j} = 2.58 \qquad (4.8)$$

$$\text{For a 99.9\%} \quad \text{"} \quad \text{"} \quad \text{"} \quad \frac{C_r}{\sigma_j} = 3.29$$

A numerical example :

(a) If the typical accuracy of handling is ± 1.00mm, this implies 1.0mm is the 3σ limit, so -

$$\sigma = 0.33$$

Letting

$$\sigma_p = \sigma_h = 0.33$$

$$\sigma_j = \sqrt{\sigma_p^{\,2} + \sigma_h^{\,2}} = .467$$

Using Equation (4.8) :

(i) For a 95% probability of success, $C_r = 0.92$mm

(ii) For a 99% probability of success, $C_r = 1.20$mm

(iii) For a 99.9% probability of success, $C_r = 1.53$mm.

(b) If the typical accuracy of handling is ± 1.50mm, this implies 1.5mm is the 3σ limit, so -

$$\sigma = 0.50\text{mm}$$

Letting $\sigma_p = \sigma_h = 0.50$

$$\sigma_j = \sqrt{\sigma_p^{\,2} + \sigma_h^{\,2}} = 0.707$$

Using Equation (4.8) :

(i) For a 95% probability of success, $C_r = 1.39$mm

(ii) For a 99% probability of success, $C_r = 1.82$mm

(iii) For a 99.9% probability of success, $C_r = 2.33$mm.

(c) If the typical accuracy of handling is ± 0.3mm, this implies 0.3mm is the 3σ limit, so -

$$\sigma = 0.1\text{mm}$$

Letting $\sigma_p = \sigma_h = 0.1$

$$\sigma_j = \sqrt{\sigma_p^{\,2} + \sigma_h^{\,2}} = 0.141$$

Using Equation (4.8) :

(i) For a 95% probability of success, $C_r = 0.28\text{mm}$

(ii) For a 99% probability of success, $C_r = 0.36\text{mm}$

(iii) For a 99.9% probability of success, $C_r = 0.47\text{mm}$.

The theory and calculations so far are independent of the nominal peg size. If cylindrical shafts of 2cm diameter are assembled into bushes, say, then if handling devices of positional accuracy ± 1.0mm are used, then for a 99.9% confidence level of assembly the radial clearance between the members would have to be at least 1.53mm. This, of course, is not practicably acceptable, because of other design constraints; yet it must be remembered that only one mode of misalignment was accounted for, if realistically all the possible deviations from the ideal state were included, the resulting clearance would have to be even larger.

So it would seem that a direct entry method of assembly is unrealistic. Alternatives are the use of chamfers to enlarge the apparent clearance, and the use of intelligence to direct advantageous reactions to contact forces, in order to achieve assembly. That is, a manipulative stage is necessary.

In conclusion, "How does the peg-hole clearance affect placement Phase I?" The answer depends on the Phase II operator, and, as reasoned, it is very likely that it will be a direct placement one. This implies that the peg must lie within the hole direct entry envelope - Figure 4.10(a). If the assembly effort is not consistently parallel to the hole axis and can deviate by up to θ radians, then the diameter of this envelope is reduced by Equation (4.1). This then is also the envelope of tolerable misalignment for the Phase I stage, for Phase I output is matched to Phase II input.

CHAPTER FIVE

JAMMING

5.1 Introduction

For slight angular misalignments a peg and hole with a judiciously selected set of parameters (geometry, friction coefficient, etc.) can be quite forgiving. Therefore, some angular misalignment is permissible even with an essentially non-intelligent placement operator. Thus, it is of interest to examine the phenomenon of jamming, and then to determine the non-jamming limits to angular misalignment.

Whenever wall contact occurs as a peg is being assembled into its hole there is a chance of jamming.

Contact with the wall of a peg, or of the hole, results from general misalignment. The misalignment could be the positional departure of the components from their ideal position, or the assembly effort direction may not be aligned to the hole axis.

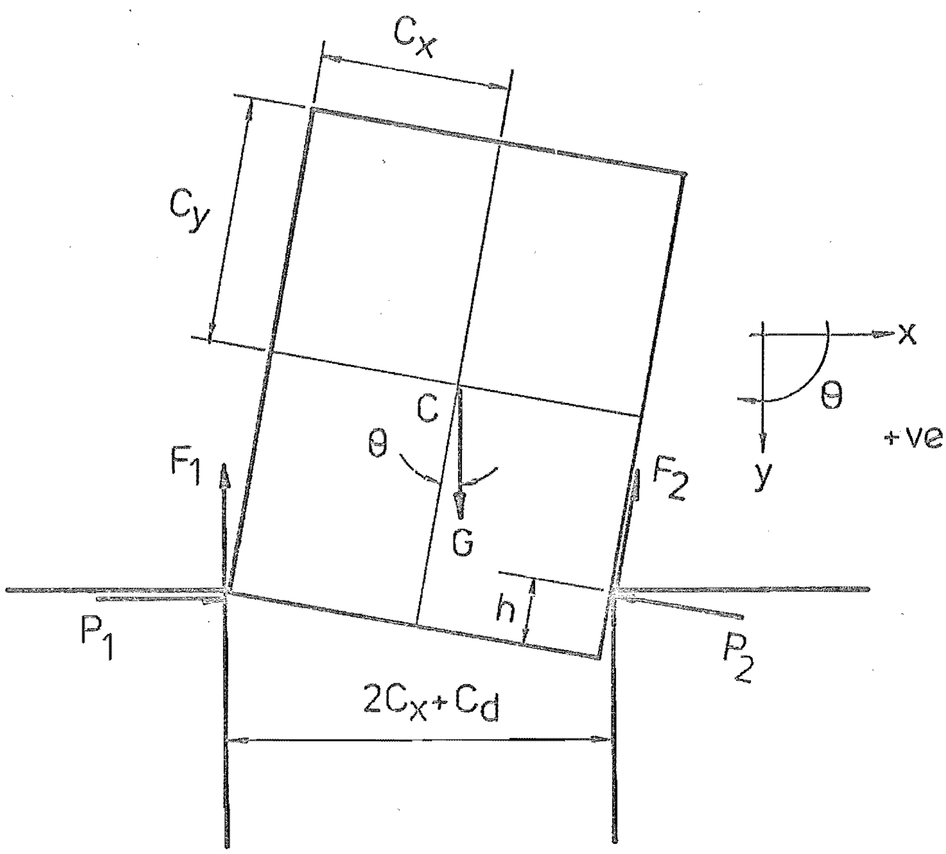
Whether jamming occurs depends on various factors, including the direction and position of application of the assembly effort, the friction factor of the contacting surfaces, the geometry of the peg, the clearance available, and the initial misalignment of the peg and hole.

An important division should be made at this point separating the two methods of assembly effort application. In one, the physical assembling effort of placement Phase II is oriented with respect to the peg, and in the other, with respect to the hole. If the placement control is peg biased, in other words, most of the essential information required for manoeuvering during the last stages of assembly is derived from peg/hole interactions as felt by the peg, then it is likely that the final assembly effort would be peg related, i.e. directed through the peg axis. A hole biased placement control condition exists when orientation information is essentially derived from the hole plane, and the peg and its holder is orientated to the hole plane as a necessary control step in the placement operation. In this case, the final assembly effort direction is likely to be parallel to the normal of the hole plane; this could be so arranged that gravity provides the assembling force.

Typically, a higher sophistication assembler using vision and tactile feedback, would use a peg biased placement control method. Sight would guide the peg nominally into the hole and tactile feedback would take over the fine manipulation, reacting to the contact forces 'intelligently' to home the peg in. The contact force would be felt through the peg, and the placement control would move the peg appropriately. A less sophisticated assembler may use a strategy of pre-orientating the peg to the hole face plane (assuming this is coplanar to the hole plane) in order to simplify the actual alignment problem. This would be termed a hole biased placement control system.

The assembly force direction then is a factor that has strong influences in the mechanics of jamming. So the study of the phenomenon of jamming will be divided into two according to this criterion: one in which the force is parallel to the peg axis, and the other in which it is parallel to the hole axis. Each area will be examined with consideration given to the relationship between the remaining variables. In this manner, quantitative values are given to the limits of misalignment for successful unaided entry. In other words, the mechanics of jamming will be examined, and the conditions for which jamming does <u>not</u> occur will be derived. Now, the maximum positional and assembly effort misalignments, for which jamming does not occur, form the outer limits of the alignment constraint envelope for which unaided assembly will be successful. Referring back to placement Phases I and

FIG. 5.1 JAMMING : HOLE ALIGNED ASSEMBLY EFFORT CONDITION



II, if Phase II is to be successful using a simple placement effort, then the positional alignment after the Phase I manipulations must fall into the same constraint envelope described above.

Graphs would be derived relating all the relevant factors influencing jamming, and from these the success, or otherwise, of the entry of a peg in a particular alignment condition could be decided.

5.2 Hole Aligned Assembly Effort Condition

The peg is to be assembled under the force of gravity, to which direction the axis of the hole is aligned. For a particular peg geometry and friction factor, the peg angle at which jamming commences will be derived. The misalignment angle is a maximum at the point of peg entry into the hole, if this is made just under the critical jamming angle (for the particular set of conditions), then the remaining assembly of the peg should be unobstructed. The angular misalignment angle is related to the peg/hole clearance; therefore, the maximum value of this angle also defines the upper limit for the clearance.

The relationship between the block geometry, the friction factor, and misalignment angle at which jamming commences, will be derived.

Reference to Figure 5.1 will reveal the diagrammatic representation of the analysed case.

Initial condition for the peg is that C_y/C_x is not large.

Resolving the forces on the peg in the co-ordinate axes directions :

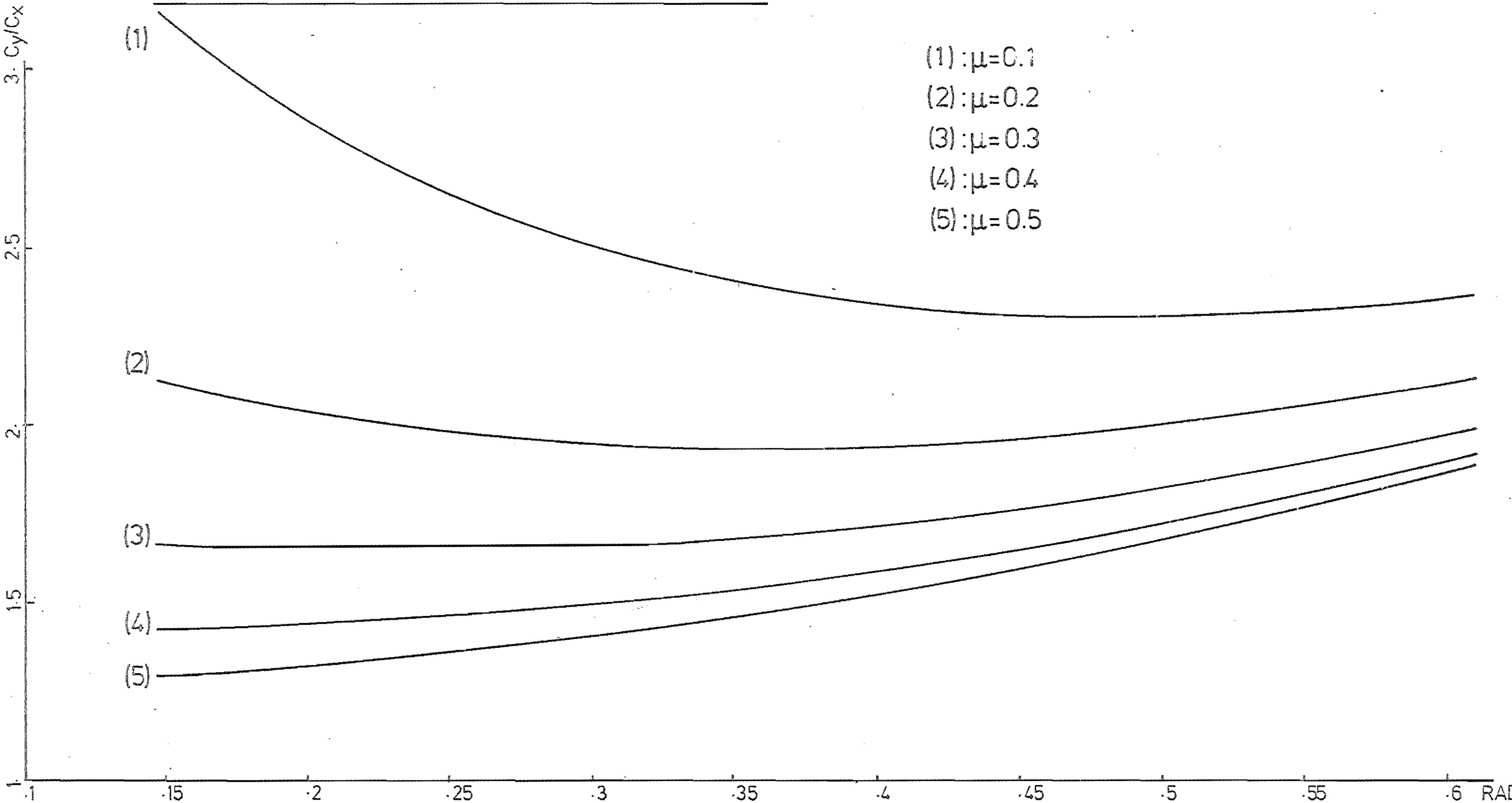
$$\Sigma F_y = G - F_1 - F_2 \cos\theta - P_2 \sin\theta - m\ddot{y} = 0, \; G = mg \tag{5.1}$$

$$\Sigma F_x = P_1 + F_2 \sin\theta - P_2 \cos\theta - m\ddot{x} = 0 \tag{5.2}$$

$$\begin{aligned}\Sigma M_c = {} & F_1 \cos\theta \, C_x + F_1 \sin\theta \, C_y + P_1 \sin\theta \, C_x \\ & - P_1 \cos\theta \, C_y - F_2 \, C_x + P_2 (C_y - h) - I_c \ddot{\theta} = 0\end{aligned} \tag{5.3}$$

FIG. 5.2 JAMMING : GRAPH OF MINIMUM PEG HEIGHT / WIDTH RATIO v. ANGLE OF PEG TILT

HOLE ALIGNED ASSEMBLY EFFORT CONDITION



m = mass of peg,

I_c = moment of inertia about an axis through C.

By geometry :

$$h = 2C_x \tan\theta \qquad (5.4)$$

Assuming the peg is in the jammed condition, then

$$\ddot{y} = \ddot{x} = \ddot{\theta} = 0 \text{ and } F_1 = \mu_s P_1, \quad F_2 = \mu_s P_2 \qquad (5.5)$$

where μ_s is the required static coefficient of friction between the rubbing surfaces.

Eliminating P_1 and P_2 from Equations (5.1) and (5.2), and substituting into Equation (5.3), with the use of Equations (5.4 - 5.5), the relation between the block geometry, friction factor, and the critical jamming angle is arrived at :

$$\frac{C_y}{C_x} = \frac{(\mu_s \sin\theta - \cos\theta)(\mu_s \cos\theta + \sin\theta) + (\mu_s + 2\tan\theta)}{1 - (\mu_s \sin\theta - \cos\theta)^2} \qquad (5.6)$$

The maximum angle of tilt, $\hat{\theta}$, is related to the diametrical clearance, C_d, in the following manner - see Figure 5.1 :

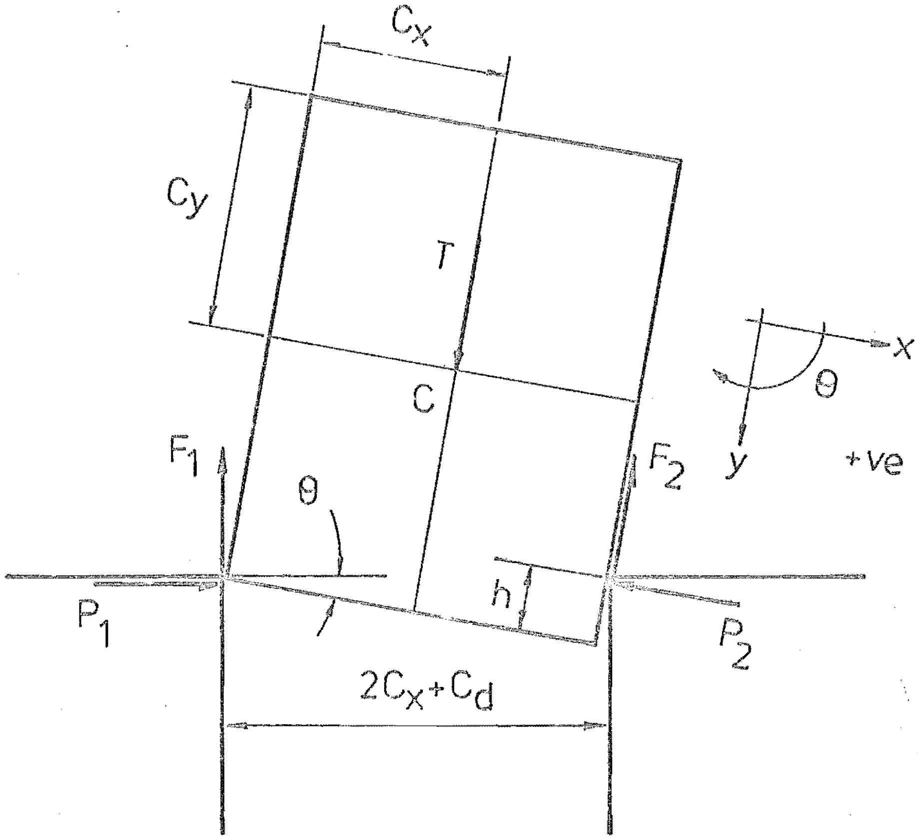
$$\cos\hat{\theta} = \frac{2\,C_x}{2C_x + C_d}$$

$$\text{i.e. } \hat{\theta} = \cos^{-1}\left[\frac{2C_x}{2C_x + C_d}\right] \qquad (5.7)$$

$$\text{or } C_d = 2C_x\left(\frac{1}{\cos\hat{\theta}} - 1\right)$$

Equation (5.6) gives the minimum peg height to width ratio, C_y/C_x, that will cause jamming for a given friction factor and peg tilt angle. Figure 5.2 shows plots of Equation (5.6) for various values of the coefficient of friction between the contact surfaces. So, if μ_s = .1 and the C_d is such that the maximum angular misalignment is .2 radians; then any peg with a C_y/C_x value of under about 2.5 will assemble without jamming.

FIG. 5.3 JAMMING : PEG ALIGNED ASSEMBLY EFFORT CONDITION



If, however, for another peg, $\mu_s = .5$ (note that the slope of this plot is in the opposite direction to that of the previous examined point), then there is always a risk of jamming. This is due to the fact that the maximum available angular misalignment always decreases with peg entry[11]. This being so means that the peg unless it is very short becomes increasingly vulnerable to jamming as it enters the hole.

If possible, the design factors should be chosen so that at the point of peg entry the maximum available angular misalignment is below the critical jamming value, and as this maximum available angle decreases as entry progresses, the peg remains in the jamming free side of the particular graphline.

5.3 Peg Aligned Assembly Effort Condition

Here the assembly effort is a force T, aligned to the peg axis. The weight of the peg is not considered as the peg will be firmly held in the operator hand. The relationship between the assembly force, the block geometry, the clearance and the friction coefficient will be derived.

The analysed model is diagrammatically shown in Figure 5.3.

Resolving the forces on the peg in the co-ordinate directions :

$$\Sigma F_y = T - F_2 - F_1 \cos\theta - P_2 \sin\theta - m\ddot{y} = 0 \quad (5.8)$$

$$\Sigma F_x = P_1 \cos\theta - F_1 \sin\theta - P_2 - m\ddot{x} = 0 \quad (5.9)$$

$$\Sigma M_c = F_1(\cos\theta C_x + \sin\theta C_y) + P_1(\sin\theta C_x - \cos\theta C_y)$$
$$- F_2 C_x + P_2(C_y - h) - I_c\ddot{\theta} = 0 \quad (5.10)$$

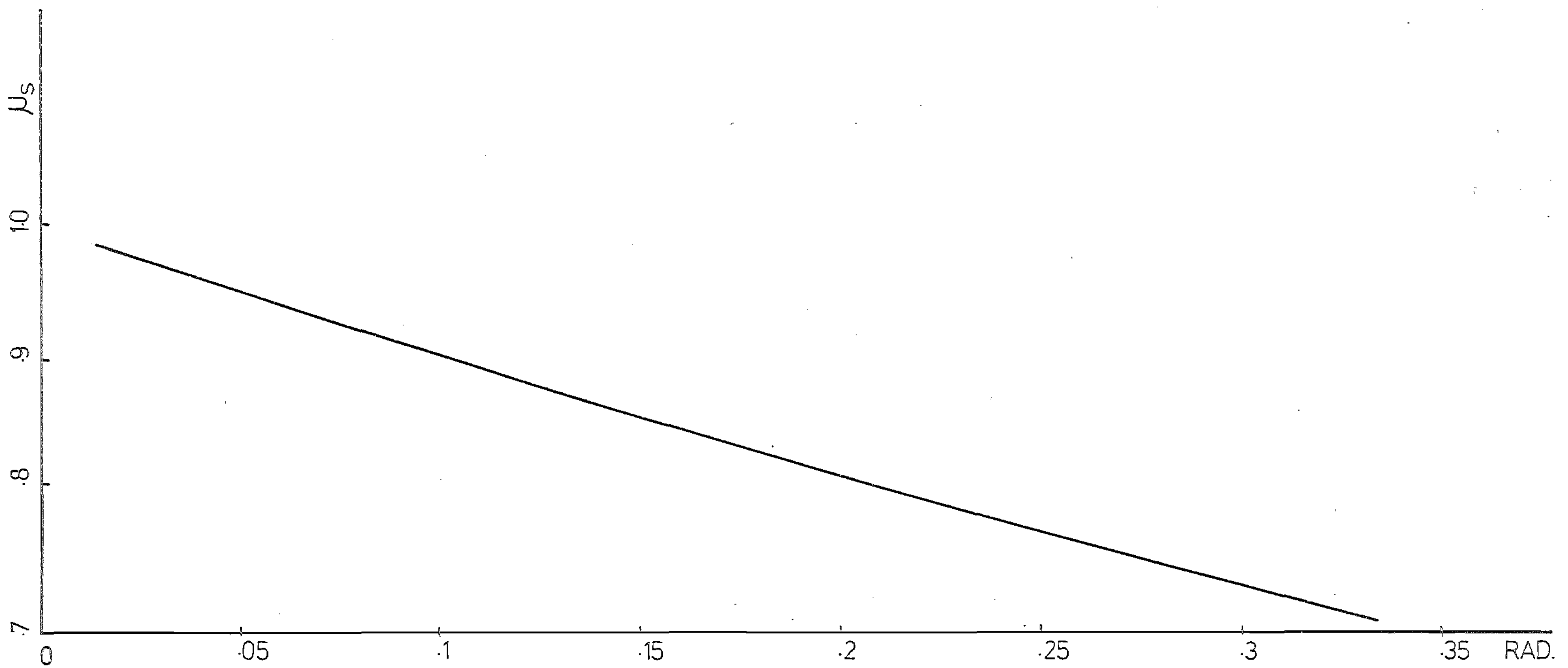
m = mass of peg,

I_c = moment of inertia about an axis through C.

By geometry :

$$h = 2C_x \tan\theta \quad (5.11)$$

FIG. 5.4 PEG ALIGNED ASSEMBLY EFFORT : JAMMING ANGLE v. COEFF. OF FRICTION



Assuming that the peg is jammed, then :

$$\ddot{y} = \ddot{x} = \ddot{\theta} = 0 \text{ and } F_1 = \mu_s P_1,\ F_2 = \mu_s P_2 \tag{5.12}$$

where μ_s is the required static coefficient of friction between the rubbing surfaces.

Substitution of Equation (5.12) into Equation (5.9) and re-arranging gives :

$$\frac{P_2}{P_1} = (\cos\theta - \mu_s\sin\theta) \tag{5.13}$$

Substituting Equation (5.13) and Equation (5.12) into Equation (5.10), rearranging and simplifying, yields :

$$\mu_s^2 C_x\sin\theta + \mu_s\sin\theta h - C_x\sin\theta = 0$$

substituting Equation (5.11) again gives :

$$\mu_s^2 C_x\sin\theta + \mu_s\sin\theta.2C_x\tan\theta - C_x\sin\theta = 0$$

$$\text{i.e.}\ \mu_s^2 + \mu_s 2\tan\theta - 1 = 0, \quad \text{if } \theta \neq 0,\ C_x \neq 0 \tag{5.14}$$

Solving this quadratic in μ_s gives :

$$\mu_s = \frac{-2\tan\theta \pm \sqrt{4\tan^2\theta + 4}}{2}$$

$$\text{i.e.}\ \mu_s = -\tan\theta \pm \sqrt{1 + \tan^2\theta}$$

$$= -\tan\theta \pm \sec\theta$$

for the positive μ_s value

$$\mu_s = \sec\theta - \tan\theta \tag{5.15}$$

Equation (5.15) is plotted in the graph on Figure 5.4, and shows that jamming in this case is not dependent on the peg geometry or the assembly force magnitude, but entirely on the angle of misalignment, θ and the static coefficient of friction μ_s. To ensure no jamming, the clearance should be designed so that the maximum entry misalignment angle is below the critical jamming angle, as specified by Figure 5.4, for a specific coefficient of friction. The maximum available angle for misalignment decreases as the peg enters, so the jamming free conditions are maintained.

The diametral clearance, C_d, is related to the maximum misalignment angle, $\hat{\theta}$, by

$$\cos \hat{\theta} = \frac{2C_x}{2C_x + C_d} \tag{5.16}$$

Rearrangement yields :

$$C_d = 2C_x(\sec \hat{\theta} - 1)$$

The numerical representation of Equation (5.15) as shown on the graph in Figure 5.4, reveals that this second method of assembly force application is more efficient than the first requiring a higher coefficient of friction to cause sticking for the same misalignment angle. Ideally then, using a peg aligned assembly effort direction, once entry is achieved, the peg should easily home without further complication.

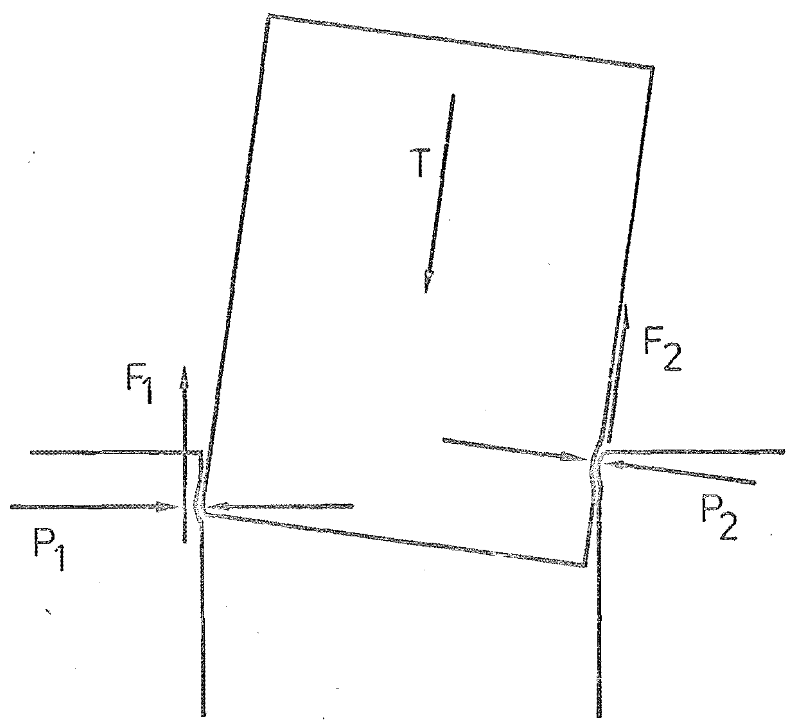
With regard to peg-hole alignment, the results derived set the limit to the relative angular misalignment of the peg and hole axes. For both methods of assembly effort application, each particular peg-hole combination has, derived from its set of relevant parameters, a maximum acceptable angle of angular misalignment. If the actual angular error is below this value then, theoretically, jamming will not occur.

The preceding two sections suggest that jamming should not be as common an occurrence as is found in practice - if the correct clearance is allowed for the particular peg geometry and friction factor; complete assembly should be automatic after the hole is found. This discrepancy is due to the fact that the above analyses are on idealised models.

5.4 Non Ideal Factors

In the idealised models used in the theoretical analyses, the

FIG. 5.5 ELASTIC WEDGING



surfaces of both the peg and the hole were assumed hard and undeformable, such that the coefficient of friction was constant. The assembled members were assumed perfectly rigid bodies. Were all assembly forces small, this might be an accurate assumption.

However, the applied forces in assembly operations can be quite high, and even if they are moderate, they can be magnified by wedging effects and impact. Since contact is usually either point or line contacts the resulting stress can be high[12]. Plastic yielding occurs readily.

Thus, jamming could result from an elastic wedging effect, or from the effects of plastic deformation of the assembly components.

Elastic wedging occurs when an applied force is large enough to cause elastic deformation at the contact regions, so internally springing the system by internal stressing, Figure 5.5. The resulting large normal contact forces, in turn, produce high frictional forces which hold the system in the wedged situation. Every assembler must have experienced the frustration, in attempts at freeing a jammed component, when a high enough applied force frees one jam only to create another in the opposite direction.

Stresses are often high enough to cause permanent deformation in the assembly components. The lips and cuts so produced then act as 'steps' to prevent any further assembly. The component must then be withdrawn, and assembly attempted again, hopefully avoiding the constriction created by the previous attempt.

Apart from the effects of high contact forces there are other non-ideal factors that arise in practice. Most of these are manufacturing inconsistencies - burrs, surface finish variations, machining marks, etc.

Therefore, besides designing away from the critical jamming region, effort must be made in the other areas of minimising contact forces and improving the quality and uniformity of the component parts.

CHAPTER SIX

MACHINE CONSCIOUSNESS AND ITS ALTERNATIVES

6.1 Introduction

In the preceding chapters the aspects of the assembly operation that are derived directly from the assembly components themselves were analysed, viz :

(1) The assembly step was divided into 'activities', and each of these was analysed to see what functional requirements they demand of an operator. Thus, the activity of placement was found to be intrinsically the most demanding in terms of operator ability. This narrowed the assembly problem into this area of fitting one component to another (peg into a hole).

(2) This led to an examination of tolerance to misalignment, and how this is affected by

(3) clearance between the assembly components, and

(4) the investigation into jamming, to find out its causing factors, and its onset, determined the limits to acceptable angular misalignment.

These findings then set out the end point conditions (as derived from the properties of the components to be assembled) that any assembly operator must meet.

The next step is to consider this operator, to consider how the assembly components are brought together, while obeying the above defined constraints, to result in assembly.

The sensing and control problems associated with this task are quite formidable. Observation of a man deftly tackling an assembly problem seems to indicate the relevance of sensing, intelligent strategy formation, dextrous manipulation and the workpiece factor of design. Since the ultimate aim is the design of a piece of machinery, or a system of machinery, to replace man in the repetitive tasks of assembly, it may prove profitable to study how an intelligent system (like man and the higher animals) relates to, and works in, its environment.

A study of this nature may reveal basic concepts of how an independent entity places itself in, and interacts with, the world surrounding it. These concepts may be applicable to all autonomous bodies, animal or machine, that work in any ecosystem.

6.2 Animal Consciousness

The definition of the concept of consciousness has always been contentious. Extensive work on this topic has been done in the areas of animal behaviour and psychology, but conclusions so far are steeped in the philosophical. However, workers in these fields generally agree that, at least, consciousness gives the entity the ability to think of itself in a situation whether any associated stimulus is present or not; i.e. the ability to reflect. Thus, in a broad sense, the phenomenon of animal consciousness is expressed as this ability of the brain to construct what amounts to a theoretical model of the world it lives in. Accordingly, in this sense, when an infant is born its conscious mind is a blank state, and as it receives stimuli from the environment it gradually builds a model of the world around it. As the child grows this model is continually updated, verified and broadened; experience is the physical interaction necessary for the continuous revision and expansion of the models of the self and environment. So, in familiar surroundings, an animal is able to model all possible strategies and actions, and evaluate them, before responding to any stimulus. For example,

FIG. 6.1 PEG AND HOLE

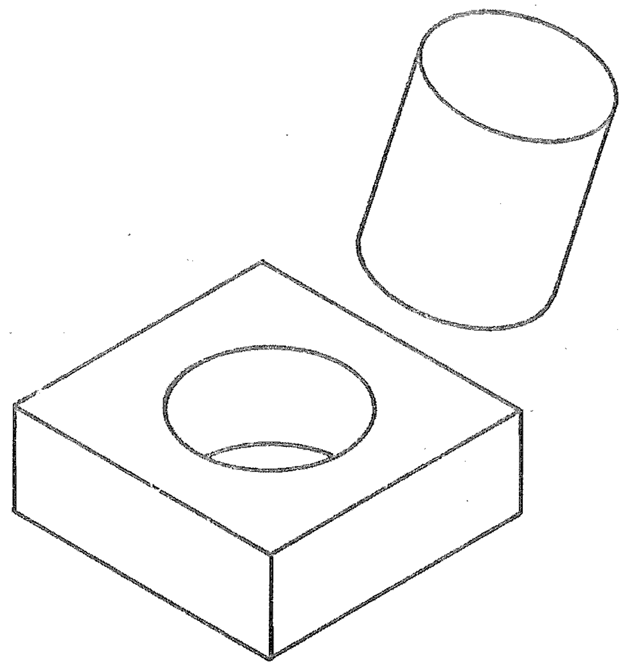
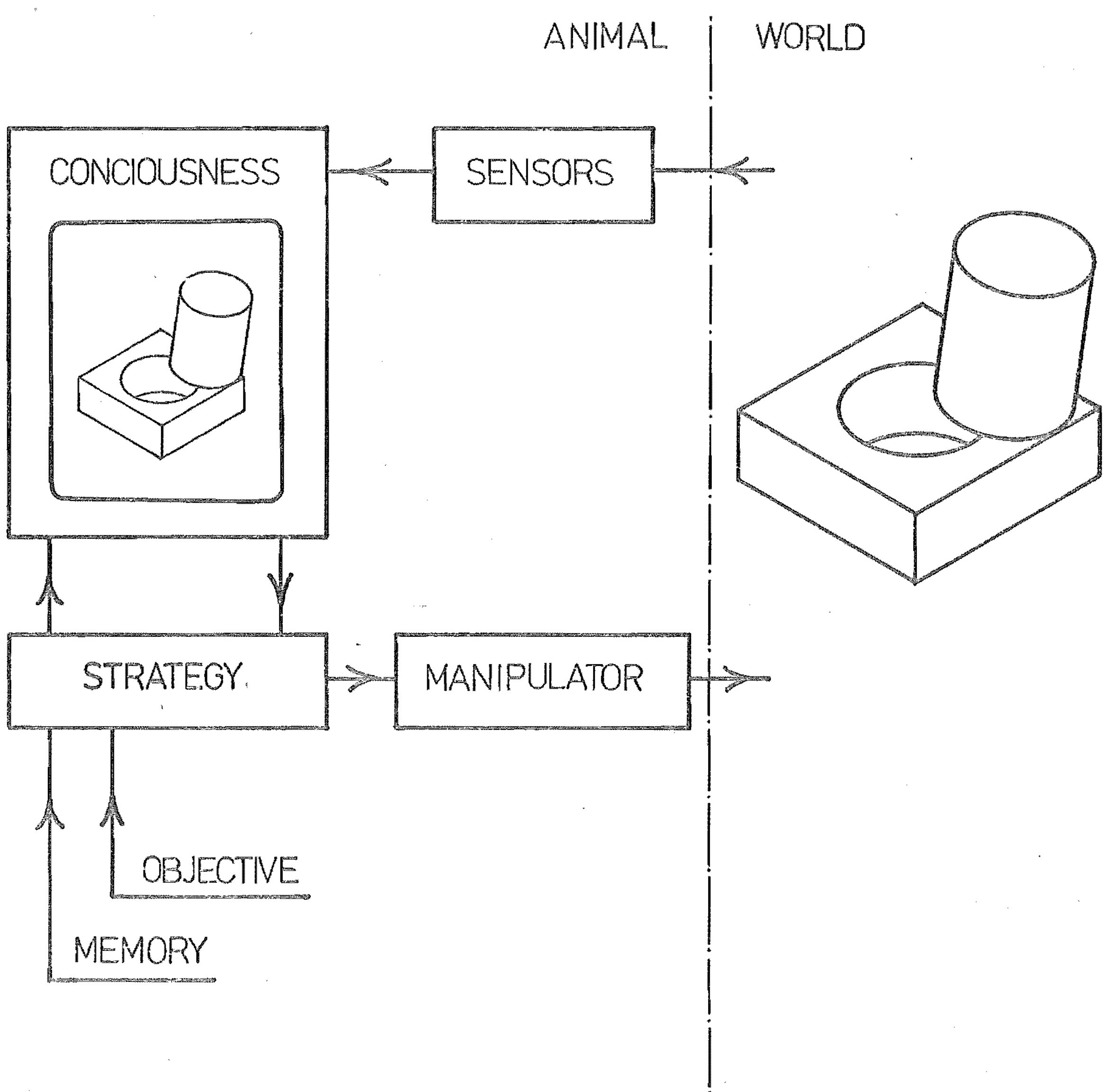


FIG. 6.2 ANIMAL CONCIOUSNESS INTERACTIVE LOOP



when an animal stalks its prey (stimulus), the place and the critical moment of breaking cover and attack is assessed from the brain's model of itself and the perceived situation. Many attacking strategies are conceived and evaluated and one is selected as the best in the given situation. The amount of experience possessed, of course, heavily influences the shrewdness of the proposed strategies, and especially in the accuracy of their evaluation.

On the highest level the brain can call on stored data to construct any situation. It can plan and scheme in the absence of the physical situation (or stimulus): that is, it can reflect.

Returning now to the problem of assembly by a human being. This is a task which, relative to the normal activities of living, is very simple, but it still contains all the essential elements of conscious modelling. Take the example of the cylindrical peg and hole situation again (Figure 6.1). Given an objective of assembly, the interactive procedure between the man and the work environment must follow this line :

(i) The man must become aware of the situation; that is, he must sense it or be told about it;

(ii) he then creates a model of the physical situation in his mind, like that in Figure 6.1;

(iii) he then works out the possible strategy, or strategies, to fulfil the objective, and selects the one he considers the best. (See Figure 6.2)

After its derivation in the mind, the solution is carried out by the physical manipulative system using a continuous feedback and modelling loop control.

It will be interesting to compare the information value of the image that a man first envisages with what can be considered to be the minimum necessary for the comprehension of a problem. The first time a man sees an unfamiliar object before working with it, he spends time exploring its details. After he has familiarised himself sufficiently with it, he monitors only the details relevant to its proper function. For example, if he is concerned with the assembly of a peg into a hole and the peg is so constrained that there is only radial misalignment, then one parameter, that is, the distance of misalignment, is focussed upon - the other surrounding features appear almost incidental.

Therefore, it follows that the conscious model does not have to include all details associated with a situation. If the problem is very simple, then only the relevant parameters need to be sensed. For example, if the problem consists of finding out whether anything rests on a platform, a complete mental model of an object sitting on the said platform is not necessary. The platform may be rigged with a binary indicator so the sensing of merely one of two states is sufficient data for the brain to determine an answer from its concept of binary states. A significant corollary is that in a mechanical system if there exists only one variable, while the rest is defined, only that variable needs to be measured for total definition of the system.

6.3 The Assembly Robot and Machine 'Consciousness'

Now, man wants a machine to do the assembly task for him. He may select from a range of machine abilities which include systems completely flexible and intelligent like the projected anthropomorphic robot, to the limited flexibility automatic machines used today for highly constrained assembly jobs.

Machine solutions can be seen as existing in a continuum of that property which appears to be similar to animal consciousness. Here it will be called 'machine consciousness'.

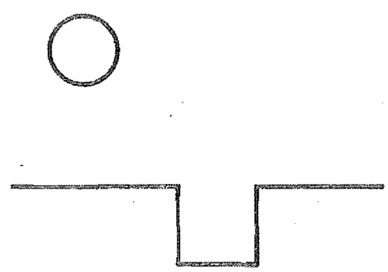
One extreme solution is for man to hand over the entire problem, lot, stock and barrel, to a machine. From the consideration of how an autonomous body interacts with its environment, this machine would have to possess similar abilities of relating. That is, it must have awareness, the ability to model the situation using the input information, and from this model plan a strategy to achieve a given objective. It is important to realise that the machine version of this process, though it may at first appear to be identical to the functions of the animal consciousness, only mimics the natural process. The mimicking ability, of course, is designed by man. A solution of this nature is said to have a high content of machine consciousness, and generally speaking, a high flexibility.

At the other end of the continuum are the solutions of low machine consciousness - that is, the simplest possible devices. These are designs in which awareness, and consciousness, is by-passed by assumptions and the by-pass is incorporated as a design. In other words, assumptions about the physical behaviour of the components of the system enable the processes of awareness, modelling and strategy planning to be embodied implicitly in the system design. This type of solution is possible only if the task to be performed is simple; that is to say, the problem is well constrained.

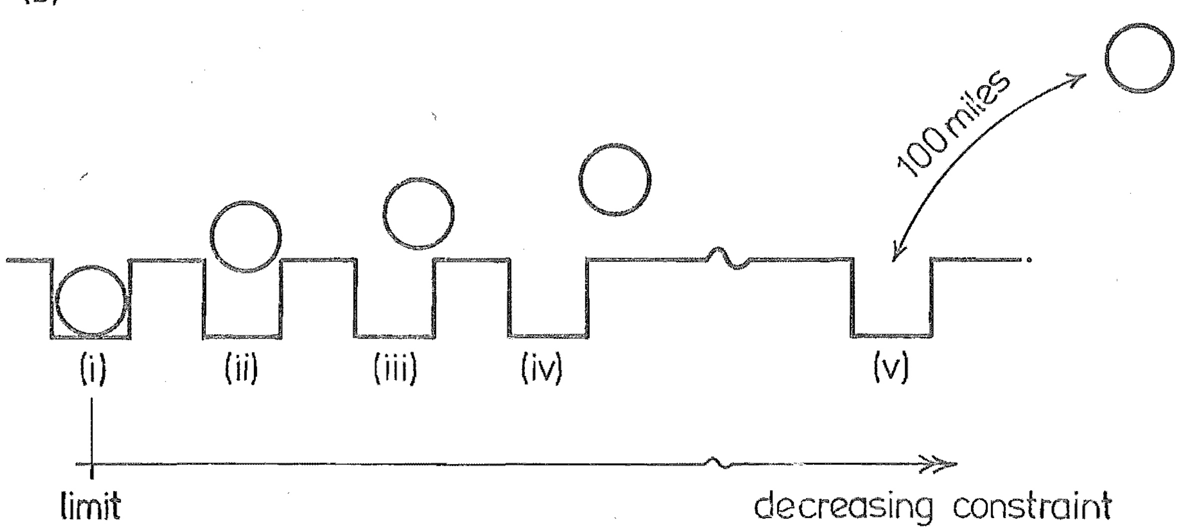
In an attempt to clarify the preceding concepts of explicit and implicit machine consciousness, an illustrative example will be taken. So that the main points of concern are not abberated by local complexities, the very simple task of assembling a ball into a hole, shown in Figure 6.3(a) will be used. Even this problem can appear with a range of difficulties (Figure 6.3(b)). The bottom limit of this range is when the ball is in its hole and towards the upper limit, the possible difficulties that could be involved are left up to the imagination, for in

FIG. 6.3 BALL AND HOLE

(a)



(b)



addition to variations in space, time can be involved. The constraint placed on the problem is regarded as the constraining limits placed on the deviation of the ball from its assembled state. So the constraint defining the positional tolerance of the ball with deviations up to that shown in Figure 6.3(b)(iii) is tighter than that in Figure 6.3(b)(iv). This gives a measure of the difficulty of the problem to be tackled.

What demands does the complexity of the problem make on the machine's ability to relate to it? As far as consciousness is concerned, none at all, for the ability to envisage a situation is independent of the complexity of the problem. It requires the same ability to model the ball directly above the hole as it does to model it 100 miles away. Similarly, for awareness and strategy planning, the ability to sense and scheme is not influenced by the problem complexity. However, technically speaking, it is easier to implement these functions in well constrained situations. For example, it is both easier to measure the displacement of the ball and conceive an assembly strategy for the situation in Figure 6(b)(ii) than for that of Figure 6(b)(v).

After this digression on constraints, return is made to the area of explicit and implicit machine consciousness. To solve, say, the problem type illustrated in Figure 6.3(b)(iv), a system involving explicit machine consciousness would perhaps take the assembly components as they are, and use either visual or tactile sensing, or maybe both, to become 'aware' of the situation. It then computes the relative displacements by the use of its internal modelling and calculative ability; then, upon deciding a strategy, call on its physical link to the outside world (its manipulators) to carry out that strategy.

A solution to the same problem using an assembly system having implicit machine consciousness, may be one in which a large chamfer is designed around the hole. All that is involved in assembling the ball is that it is placed on the chamfer.

To explain this further: for a start, the ball and chamfered hole must be viewed as a system solution to the problem of assembling a ball into a hole. Another system solution is the above described 'conscious' robot one. In an implicit machine consciousness solution, the designer has gone a bit further than designing a machine that is able to cope with a wide range of problems; he has gone on to delve into the specifics of an actual problem. Logically, a bias into the details of one problem type is traded off against the flexibility of the solution. So, as was mentioned earlier, this type of solution is applicable mainly to problems of high constraints. For example, singular modes of misalignment problems. The designer considers the whole system: designs the manipulating machine and modifies the assembly parts so that the predicted interactions will automatically achieve the problem solution. For the problem in Figure 6.3(a), the ball is dropped onto the hole chamfer and it rolls into the assembled position. The designer knows that when the ball contacts the chamfer it will sense an unstable state: this state automatically offers a strategy, and the ball rolls home. This consciousness - sensing, modelling and strategy - is incorporated by the designer in the interacting geometry. In other words, it is implicit in the system design.

Because of its very nature, the 'implicit' type of solution relies on many assumptions. For the ball and chamfer problem, besides constraining the placement of the ball to within the chamfer perimeter, assumptions of gravity direction, ball sphericity, chamfer surface, uniformity, consistency of the physical system (rigid arms, etc.), absence of obstacles, (rubbish, glue, magnetic effects, etc.) must all be maintained.

Typically, a solution of the implicit machine consciousness type is less expensive in capital and running costs than a system involving a high order of explicit machine consciousness. Therefore, judging on an economic criterion, the less expensive solution is more desirable. However, if the problem is not constrained to an extent that makes an explicit type solution easily derivable (usually because of economic restriction in other areas), a system solution that is a composite of explicit and implicit machine consciousness components will have to be used.

Explicit machine consciousness solutions generally imply problem flexibility; the implicit machine consciousness solutions are usually confined to highly constrained problems. So, a balance must be struck between flexibility and simplicity. It was said that generally the less complex implicit system solutions are applied to highly constrained problems (e.g. peg/holes with only slight radial misalignment) at the same time, it is noteworthy to realise an important point, and this is the fact that the flexibility of the solution is only limited by designer ingenuity.

In conclusion, a lot may be said on behalf of the implicit machine consciousness type of system solution. Besides possessing an appeal in the light of conceptional simplicity, if its flexibility can be slightly increased beyond that which its past representatives have displayed, then this concept may provide an ideal solution for the robotic problem. This is especially so if the view that a completely anthropomorphic robot is not really necessary, but that a far more simple machine with a talent for dealing with small variations is adequate. This then provides the basis for continuing work in the area that is, at the moment, represented by chamfers and simple spring loaded assembly heads.

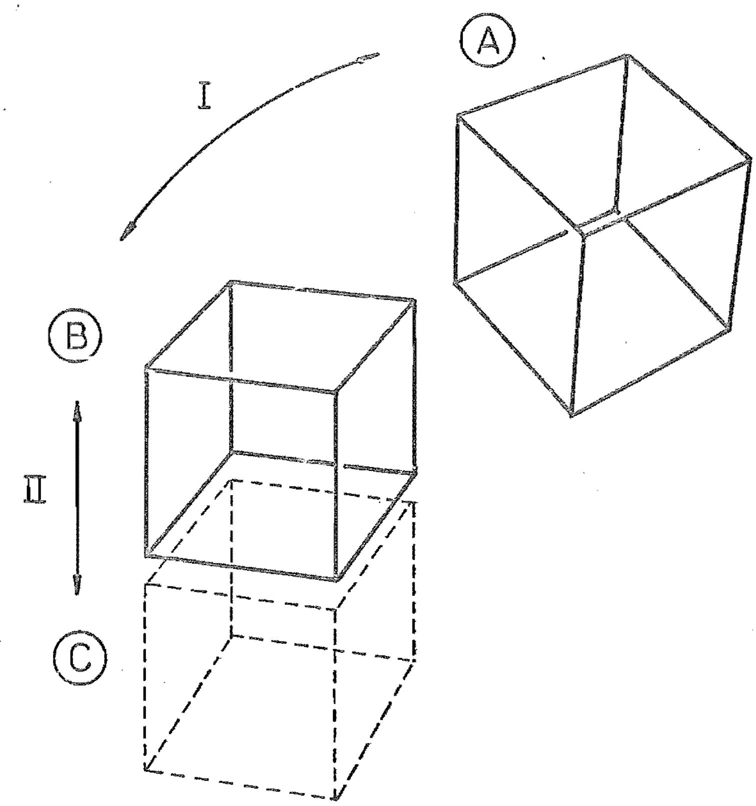
CONCLUSION TO PART ONE

In this conclusion, following the preliminary study into the definition of the assembly problem and how it affects a solution, the preceding elements will be related. The work into the assembly step, misalignment, and clearance, will be fitted into the general plan of study of this project.

In this examination of the basic problem area, Chapter 3 began with the rationalisation of the operational step of an assembly operation into the activities of pick-up, carry, placement and return. Next to be introduced was the concept of behavioural demands on the operator by the operation to be performed through its objectives and the physical elements involved. These demands on the operator that must be met for the successful execution of each job, can be expressed as a combination of both operator intelligence and physical dexterity.

An analysis of the activities of the assembly operational step showed that each activity is performed within a particular set of constraints. Some of these constraints are a function of the assembling system used; others are defined by the parts to be assembled. The demands placed by the activity of placement, or the fitting of a part into its assembled position, is a function solely of the geometrical relationship between the assembly components themselves. Whereas in the other activities the extent of the demands, or the tightness of the constraints on the operator dexterity, can be mollified by wise operator systems design because they are a function of both the work components <u>and</u> the operating system. Therefore, because for a typical assembly the clearances between the adjoining parts are very small, the positional constraint envelope for successful placement is correspondingly tight, consequently the behavioural demands placed by this activity on an operator are high.

FIG.3.6 THE PLACEMENT STAGE



A → B : PLACEMENT PHASE I
B → C : PLACEMENT PHASE II

So in Chapter 3 this conclusion was derived: the main difficulty in the assembly operation lies at the assembling interface where the components are fitted into their assembled positions. This phase of the operation is the most difficult because the placement activity here demands a high level of operator ability for success. It was found that these demands arose from the workpieces, or assembly components themselves, so it will be of interest to explore and quantify these demands. This led to a detailed study of alignment and clearances.

The placement stage of an assembly step is illustrated in Figure 3.6 (appearing again overleaf). Placement Phase I (from positions A to B) is an alignment and manipulation activity. This is the crux of the assembly problem; it will involve short range sensing and subsequent fitting, an attempt at finding a solution is the subject of the following section - Part Two. However, affecting this next area of study is Placement Phase II (from positions B to C), because Phase II follows directly after Phase I. So, if due to placement conditions, for Phase II to be successful, the allowable misalignment at B is defined by certain positional constraint envelopes, then these constraints affect the Phase I operator in that they define the Phase I end conditions. In other words, the two placement phases must be matched.

Hence, in Chapter 4, the positional constraints on the element at B are related to the relative geometry of the components to be assembled. In other words, the concern is - 'What is the maximum misalignment that B can have and still be assembled?' At this stage a lack of defined concepts led to a digression on the various modes of misalignment, reference alignment positions, and the prerequisite conditions for entry in the case of mating assemblies. However, it was found that whether Phase II is successful depends on these following factors: the proximity of position B to its ideal position; the intelligence of the operator;

and that the degree of each of these that is required is a function of the geometric properties such as clearance, shape, and the friction coefficient.

This implies that to assemble a particular set of components an operator of a certain ability, as defined from the component parts themselves, is necessary. This ability can be made up of intelligence and/or manipulative dexterity, in any proportion, so long as the total ability is at least comparable with the difficulty of the job. However, as far as the positional constraints at B are concerned, the smaller the proportion of intelligence in an operator, the tighter are the constraints at B (that is, the component at B must be closer to the ideal position). This affects Phase I.

For instance, take the assembly of the cube in Figure 3.5. If a system of great ability, say a man, is given the task of being the placement Phase II operator, then his intelligence is such that the positional constraints for the assembly component at the stage B can be so wide as to be almost non-existent, and still placement will be achieved. Correspondingly, the constraints upon the preceding Phase I operation is also low. On the other hand, if a mechanism of meagre intelligence that does little more than place the cube in a certain direction is used as the Phase II operator, then the aspect of the positional constraints at B becomes acute. If, say, the direct placing effort is parallel to the hole axis, then for successful assembly, the cube at position B must lie within the square sectioned envelope projected above the cubic cavity. The size of this envelope, and thus the limits to misalignment at B from the ideal position is dependent on, and is of the same order of magnitude as the clearance between the peg and the hole. For this Phase II operator with its very narrow tolerance band to deviations in the initial (or input) position B,the component must be supplied (by

Phase I) with a corresponding accuracy. For a slightly more intelligent operator (say one that can react against jamming once entry is achieved), the tolerance for the B positioning is correspondingly higher. So that, given the operator intelligence and the placement effort direction and variability, the positional constraint envelopes at B can be determined.

So reiterating the concepts of Chapter 4, it can be said that putting constraints on deviations of position B from its ideal position (in order that Phase II is successful), at the same time implies constraints on the final positioning of placement Phase I. In fact, for a known Phase II operator intelligence, the demanded accuracy of the Phase I final positioning is computed from the tolerance to misalignment at B; that is acceptable to the Phase II operator. Thus, the assembly components, in this manner, define one of the constraints on the Phase I operator.

It is probable that the placement Phase II operator will be a direct placing mechanism of little intelligence (the intelligence being incorporated in the preceding step - in the Phase I operator). Therefore, it will be of interest to determine the limits of B misalignments for which direct insertion is successful. This leads to Chapter 5 on the subject of jamming.

The two situations of a hole aligned and a peg aligned assembly effort were analysed and the limits of misalignment for which jamming does not occur were derived. These limits are a function of both the assembly geometry and the friction coefficient of the contact points. So derived is the angular misalignment envelopes at B, acceptable by a direct insertion Phase II operator. These then are also the angular misalignment envelopes for the final positioning by the adjoining Phase I operator. The envelopes are unique for each assembly geometry and friction factor.

An illustration will show how these misalignment envelopes may be used. If assembly of the peg is to be by insertion along the hole axis, then for success the peg must lie within the envelope projected axially above the hole. Within this envelope the misalignment may take any form. The other situation is when the peg may be slid along the hole plane in search of the hole; here the angular misalignment envelope dictates what angular deviations between the peg and hole axes are allowable.

Now that the aspects of the job that directly affect the operator have been defined, the next area of interest is the nature of the operator itself. Chapter 6 delves into the nature of autonomous effector systems - man, animals, etc. - and draws parallels to an assembly operator, the conception and design of an assembly system being involved. In this assembly system the operator is a major component. Also discussed are the concepts of implicit and explicit machine consciousness and their expression, and implications, as solution systems.

P A R T   T W O

BODY CONTACTS AND TACTILE SENSING

INTRODUCTION TO PART TWO

Part I of this study examined the problems of assembly and isolated its most difficult activity. This activity - the one of fitting a component into its assembled positon - was further explored with regard to operator demands and was found divisible into two phases. Phase I was the sensing of, and alignment with, the hole; Phase II, the final insertion. A detailed study into the mechanics of Phase II resulted in positional constraint envelopes (which are dependent on assembly component geometry and operator intelligence) for the alignment of Phase I.

In Part II of this study the solution to problems of Phase I will be investigated.

The problem, as defined in Chapter 3, is the assembly of a component when presented in close proximity to its assembled position, but it is subjected to random misalignments. As a first stage of study, the problem of the assembly of a cylindrical peg into a hole was taken, both as a commonly occurring real assembly situation, and as a reasonably elementary, though a primary form, from which derived knowledge could have relevance for other secondary and more complex shapes. Thus, the problem is the assembly of a peg into its hole when presented in close proximity to its entry position, but subjected to random misalignment. Positional misalignment would be less than 1 cm, and angular misalignment under 30°; these are wide deviation limits even for most presently available 'robotic' transfer arms and crude versions of long range sensing and manipulation devices.

The questions that are now raised concern the mode of sensing to be used. For, as was discussed in Chapter 6, the operator must <u>sense</u> the problem before a solution can be attempted. The sense of tactile feedback has been chosen in this project as the area that firstly bears deeper investigation, and secondly, as the most likely to yield a suitable solution. The reasons for this approach will be discussed now.

Firstly, a consideration of the methods by which a human operator would assemble a peg into a hole will reveal that he uses two modes of sensing. For long range sensing and general orientation, vision is used. But when it comes to fine manipulative work, when the acuity of the visual sense is insufficient to cope with the 'smallness' of the movements, tactile sensing takes over. For the process of fitting components together, if the parts are supplied approximately in their assembled position, then there is doubt whether a blind person would be any less efficient than a sighted one for doing the job. Certainly, there is a high reliance on the sense of touch in exercises such as that described above. The function of the brain should not be forgotten.

Secondly, as was shown in Chapter 4, there is a high probability of extraneous peg-hole contacts during the fitting or placement operation before assembly is completed. So why not use these as the sensing medium? An examination into the mechanics of contacts may reveal expedient solutions to the problem.

Thirdly, the use of tactile sensing could mean that only the assembly components themselves are involved, and that expensive and cumbersome auxiliary equipment may not be necessary.

And fourthly, it is hoped that through the use of tactile feedback, a simple solution system of mid-range explicit machine consciousness (Chapter 6) can be devised to possess reasonable flexibility.

But the first area of study is the phenomenon of contacts: to relate the modes of misalignment to contact force directions and moments.

Once armed with these basics it is hoped that a solution may evolve.

CHAPTER SEVEN

PEG-HOLE CONTACTS

7.1 Introduction

The study of the mechanics of body contacts, and what happens at a contacting point, is aimed at elucidating the behaviour of the peg and hole system at the assembling interface. The understanding of the reactions during this placement stage will provide greater insight into the mechanics of assembly, through which, hopefully, a solution to the assembly problem will be achieved.

It is envisaged that body contacts will give rise to reaction forces and moments that are a function of the mode of misalignment. The aim is to be able to use these reactions for component alignment.

However, first of all, the nature of contact forces must be investigated. Relations between the contact force, magnitude and direction, and other relevant parameters like contact geometry, forcing effort, and contact friction must be derived. This will be done through the theoretical modelling of the peg-and-hole situation.

7.2 Body Contacts

As a preliminary step it is necessary to establish the system behaviour when a body (a peg) comes into contact with another body (a hole) under the influence of a system of forces.

Consider the system shown in Figure 7.1(a), defined by the boundary S, containing a gripped peg. At A the system is attached to some form of manipulator, and here, only the force and moment that act at this interface is of concern. Acting elsewhere through the system boundary are contact forces and moments.

FIG. 7.1 THE PEG SYSTEM

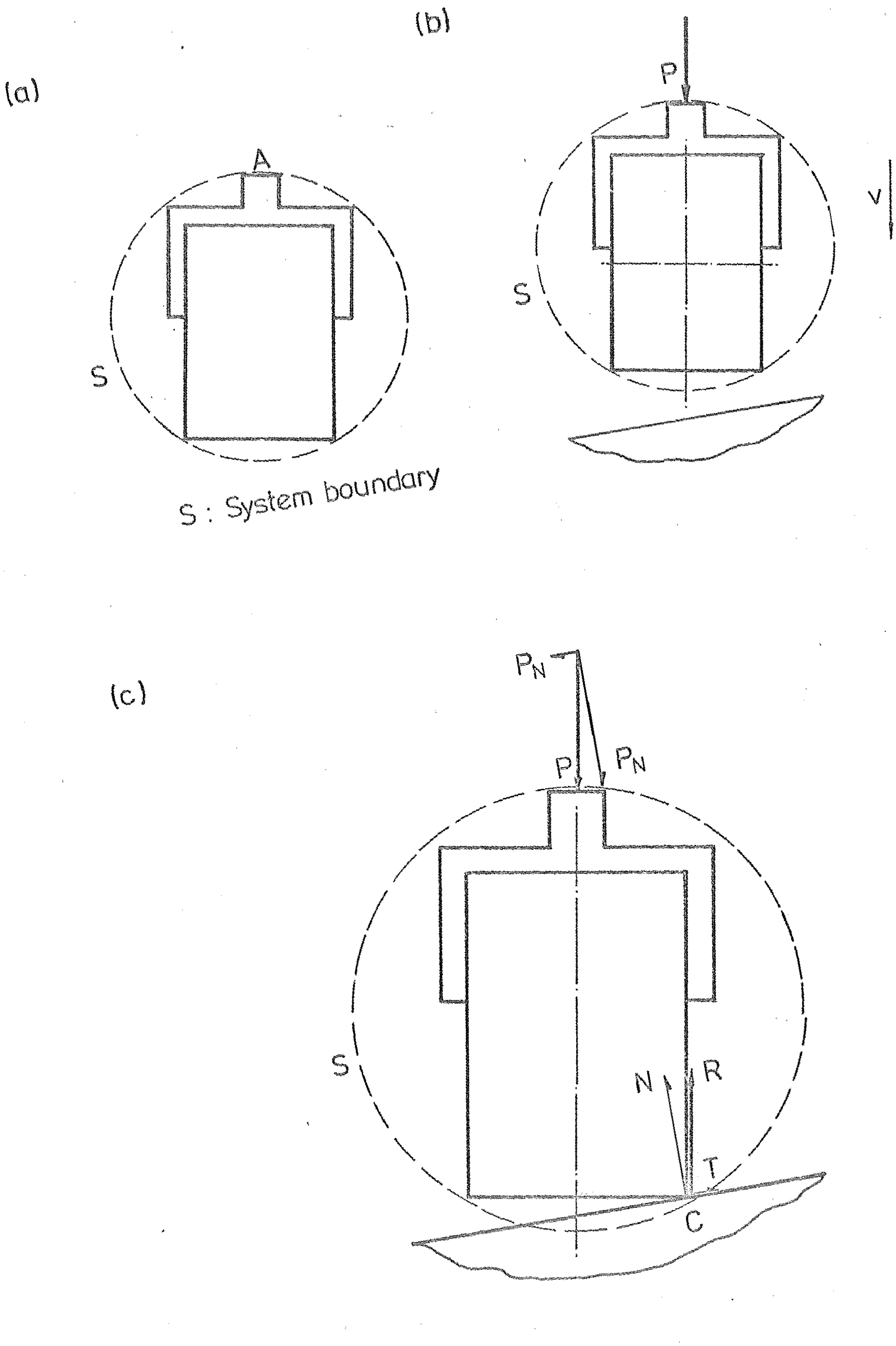
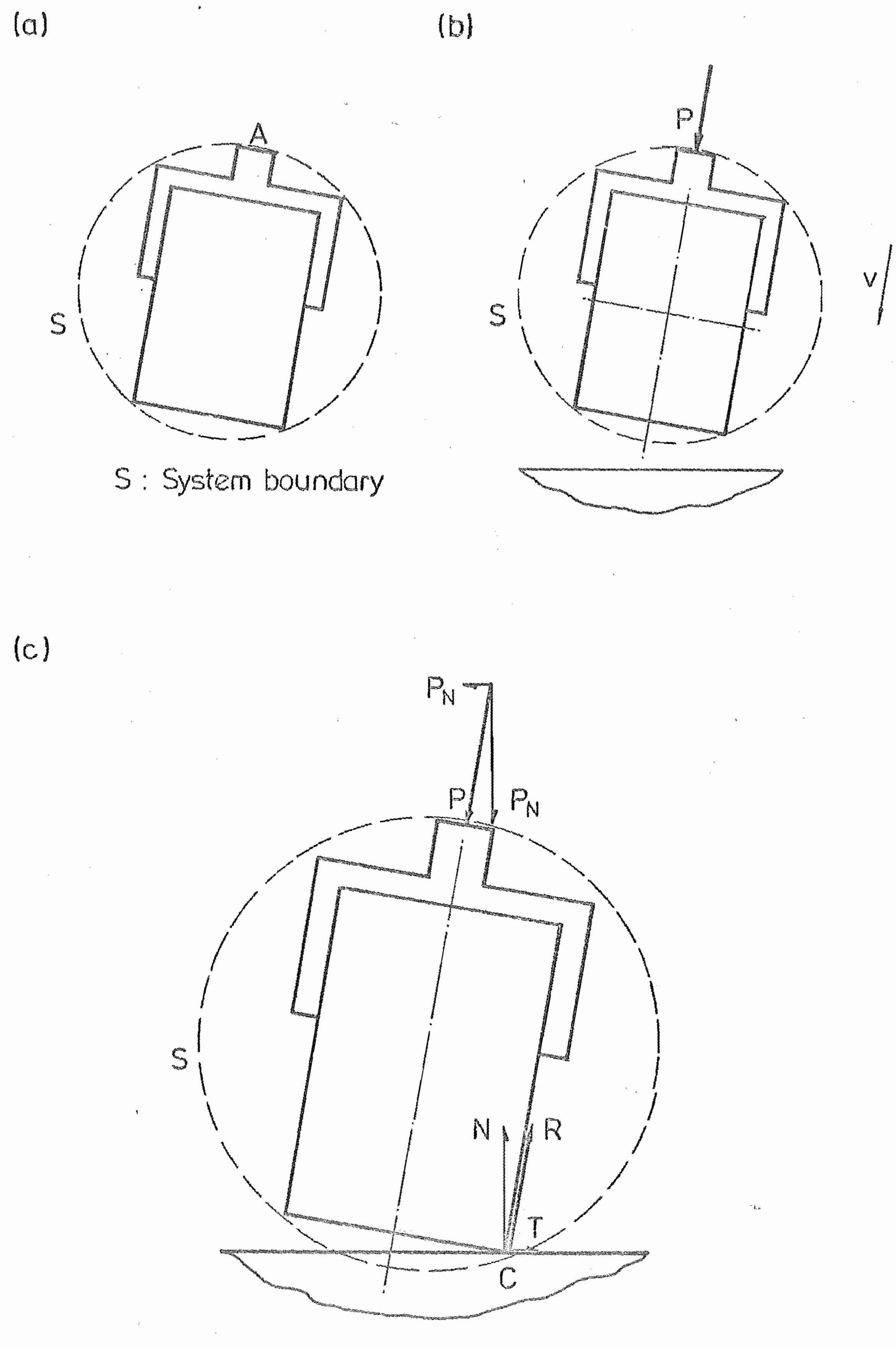


FIG. 7.1 THE PEG SYSTEM



For the system S, the following holds -

$$\Sigma\text{Forces} = 0, \quad \Sigma\text{Moments} = 0 \tag{7.1}$$

If there is no motion, all the forces and moments acting on the system are external; if there is motion, then internal body forces and moments are involved.

When is the contact stable, and when is motion involved? To answer this, consider the force P acting on the system at the manipulator interface A: Figure 7.1(b). The system will move in the direction of P until contact is made with the plane at C, at which time and place a reaction force, R, will arise to oppose P: Figure 7.1(c).

The direction of R is dependent on the contact geometry, the friction coefficient at the contact point, and the direction of P. This reaction force R, which is generated by P, can be seen as a resultant of two components; a plane normal component, N, and a plane tangential component, T.

Returning to the forcing effort P, it is seen that P is also resolvable into two components with respect to the plane normal and plane tangential directions, into P_N and P_T respectively. P_N is balanced by the contact reaction normal N, and P_T is balanced against the contact reaction tangential T, so that :

$$N = -P_N \tag{7.2}$$

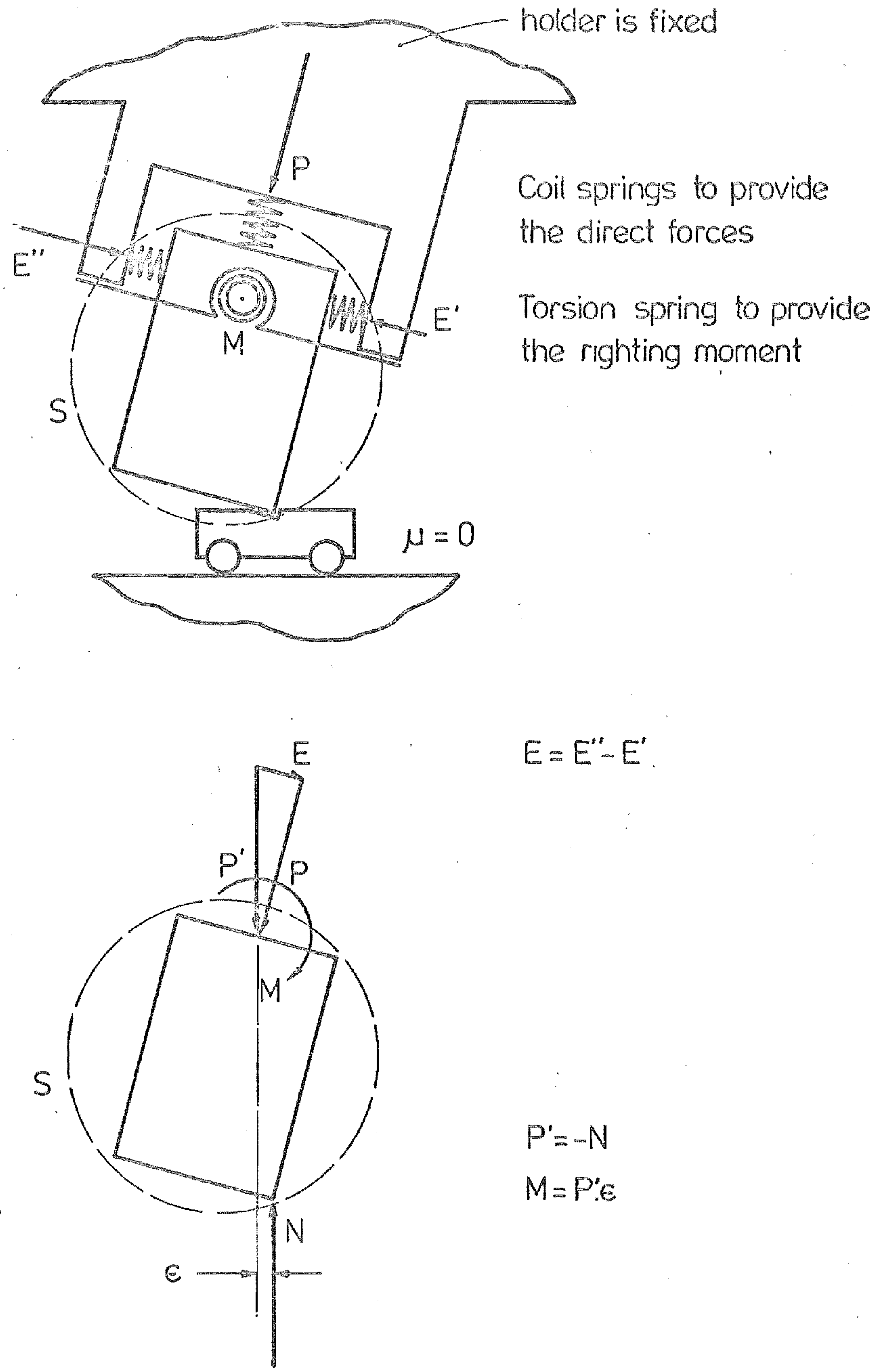
$$\text{and } T = -P_T \tag{7.3}$$

However, whereas Equation (7.2) always holds, Equation (7.3) does not, for the magnitude of T is upper bound such that

$$T_{max} = \mu N \tag{7.4}$$

where μ is the coefficient of friction at the contact point. Therefore, as P deviates increasingly from the plane normal direction, and its P_T component grows, when P_T surpasses T_{max} in magnitude, T can no

FIG. 7.2 ARRANGEMENT OF FORCES IN A MOTION CONSTRAINED SYSTEM



longer match it, so a net tangential force ΔP_T results, where

$$\Delta P_T = P_T - T_{max}. \tag{7.5}$$

In other words, if the direction of the forcing effort P lies within a right cone of semi-angle $\alpha_f = \tan^{-1}(\mu)$ rad. aligned with its axis parallel to the contact normal direction, then it can be completely balanced by the reaction force R.

Otherwise, it will lie outside this 'cone of friction', such that $\Delta P_T \neq 0$, then one of two things will happen:

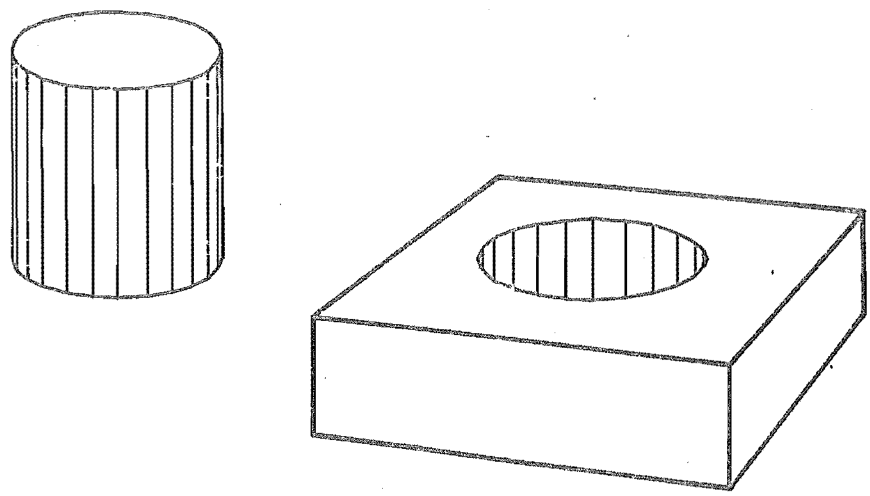
(i) If the applicator of the forcing effort P is completely free to move (or perhaps servoed off the contact forces), the system S would translate under the influence of ΔP_T. A balance of forces still leaves a system of moments which may not be balanced, so if not constrained, pure rotation will occur. Complete force and moment balance is then achieved through the inertial body force and moment developed.

(ii) If the applicator of the forcing effort P is not free to move, but appears to remain stationary, holding a constant attitude, then the direction of P must change. The force and moment balance on the system is achieved through the rearrangement of forces in the elements of the applicator or arm remote from the system S such that the direction of P lies within the contact cone of friction. This force rearrangement is usually attained through the flexing and stressing of the arm elements. The moment balance is similarly achieved and is supplied as a bending moment at the system/manipulator interface A. A consideration of Figure 7.2 will clarify this second situation.

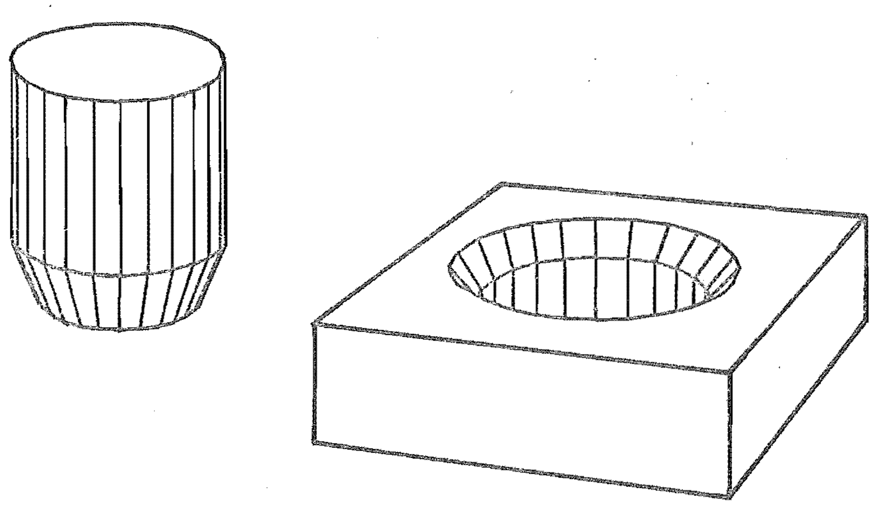
The first situation can be used to advantage if the resulting motions can be directed so as to aid the assembly of the components. Perhaps

FIG.7.3 PEG AND HOLE MODELS

(a)



(b)



the interacting geometry could be designed to accentuate the unbalanced tangential force ΔP_T for this purpose. This aspect of body contact will be examined in Chapter 9.

The second situation where the contact remains stationary is more conducive to use in tactile sensing. The consideration of contact forces and moments for tactile feedback appears in Chapter 8.

However, whichever aspect of contact is of interest, a common factor exists - the contact normal. In both situations the direction of the contact normal is important. This direction is directly related to the interacting geometry.

The various contact forms of a peg with a hole will now be surveyed, and the associated contact normal directions derived.

7.3 Types of Peg-Hole Contacts

As a preliminary step the models of the peg and the hole, and some of the terms to be used, will be defined.

The cylindrical peg and hole is modelled as shown in Figure 7.3(a) to be made up of a very large number of flat planes, and the chamfers as in Figure 7.3(b) comprising of a very large number of symmetrical trapezia. Consequently, the types of contact are confined to the following :

(i) Line/line

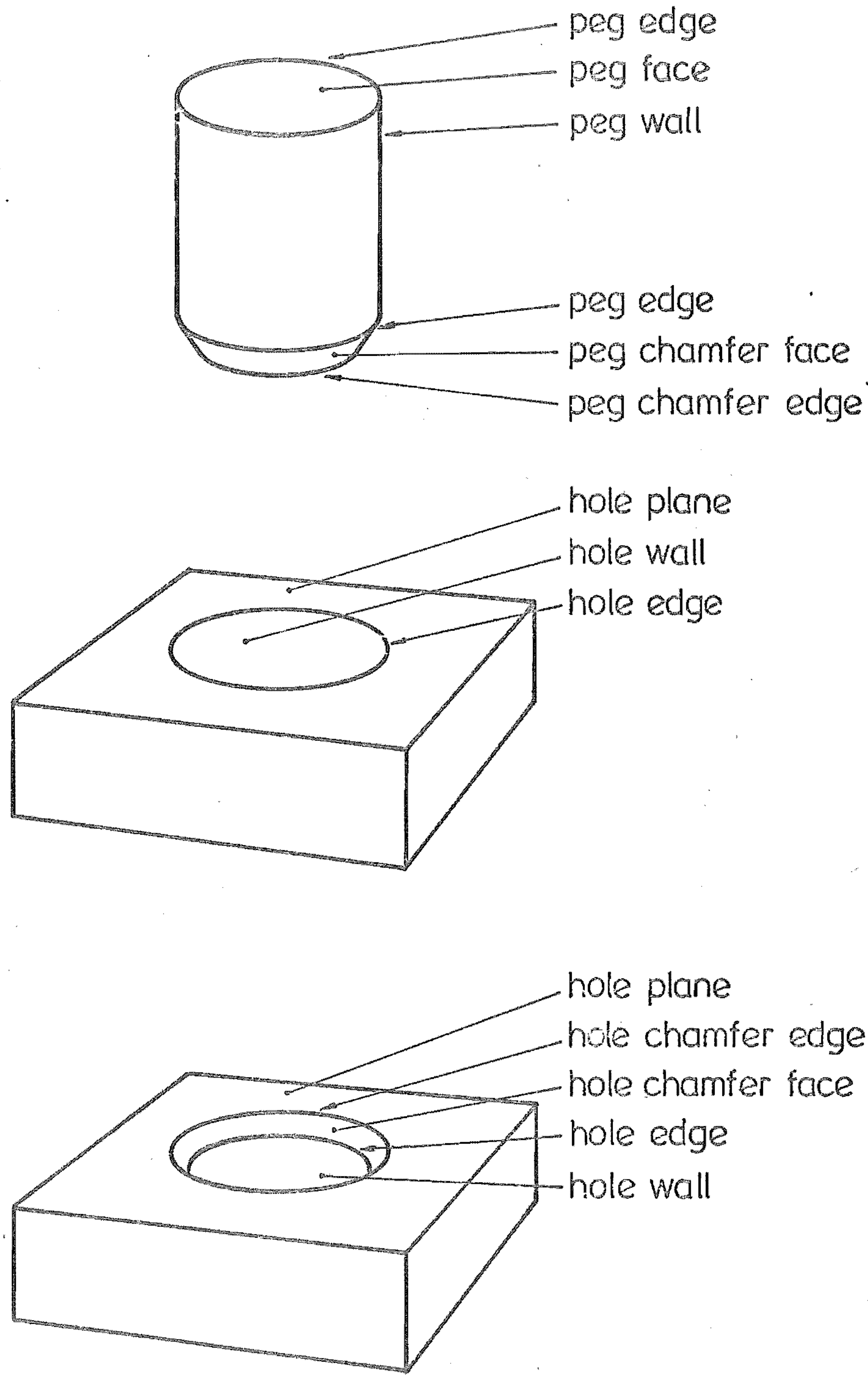
(ii) Line/plane

(iii) Plane/plane.

Some of the terms used to describe the various elements on the peg and the hole are described in Figure 7.4.

The various peg and hole forms will now be surveyed and the associated possible contact forms derived. That the diameter of the peg is less than that of the hole is a primary condition.

FIG. 7.4 PEG AND HOLE TERMS



1. <u>Unchamfered peg - unchamfered hole</u>

With a sharp edged cylindrical peg assembling into an unchamfered hole, the following contact forms may arise :

(i) Line/line contact; (a) peg edge/hole edge

(ii) Line/plane contact; (a) peg edge/hole plane

(b) peg edge/hole wall*

(c) peg wall/hole edge

(iii) Plane/plane contact; (a) peg face/hole plane

(b) peg wall/hole wall.

2. <u>Unchamfered peg - chamfered hole</u>

The following contact forms may arise :

(i) Line/line contact; (a) peg edge/hole chamfer edge

(b) peg edge/hole edge

(ii) Line/plane contact; (a) peg edge/hole plane

(b) peg edge/hole chamfer face

(c) peg edge/hole wall*

(d) peg wall/hole edge

(e) peg wall/hole chamfer edge.

(iii) Plane/plane contact; (a) peg face/hole plane

(b) peg wall/hole chamfer face

(c) peg wall/hole wall.

3. <u>Chamfered peg - chamfered hole</u>

The following contact forms may arise :

(i) Line/line contact; (a) peg edge/hole chamfer edge

(b) peg edge/hole edge

(c) peg chamfer edge/hole edge

(d) peg chamfer edge/hole chamfer edge

(ii) Line/plane contact; (a) peg edge/hole plane
(b) peg edge/hole chamfer face
(c) peg edge/hole wall*
(d) peg chamfer edge/hole plane
(e) peg chamfer edge/hole chamfer face
(f) peg chamfer edge/hole wall*
(g) peg wall/hole edge
(h) peg chamfer face/hole edge
(i) peg wall/hole chamfer edge
(j) peg chamfer face/hole chamfer edge

(iii) Plane/plane contact; (a) peg face/hole plane
(b) peg chamfer face/hole plane
(c) peg chamfer face/hole chamfer face
(d) peg chamfer face/hole wall*
(e) peg wall/hole wall.

4. <u>Chamfered peg - unchamfered hole</u>

The following contact forms may arise :

(i) Line/line contact; (a) peg edge/hole edge
(b) peg chamfer edge/hole edge

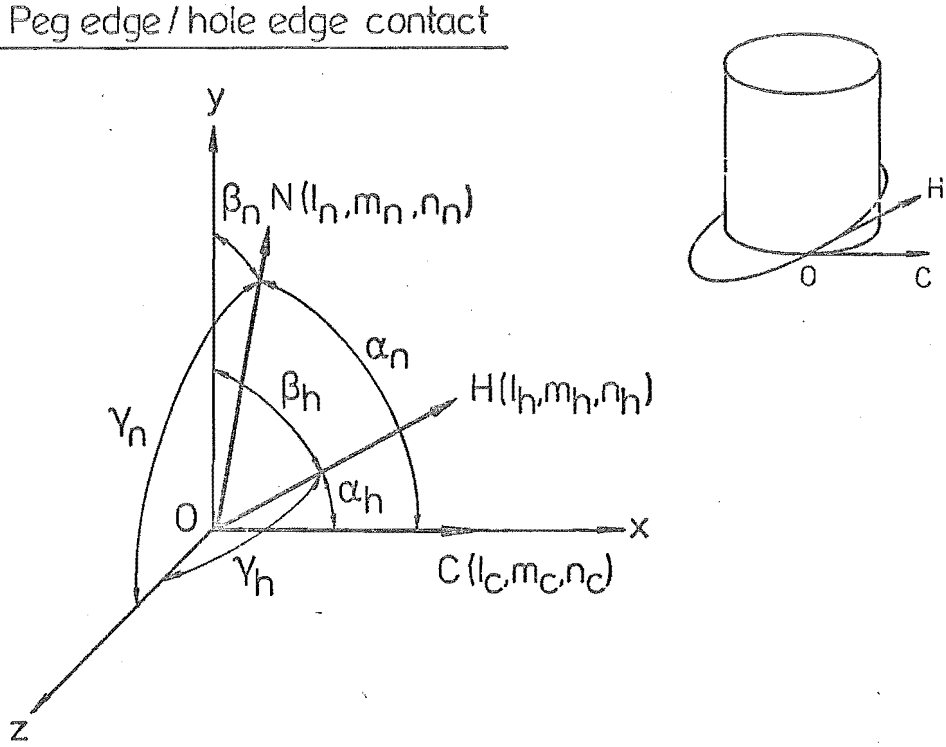
(ii) Line/plane contact; (a) peg edge/hole plane
(b) peg edge/hole wall
(c) peg chamfer edge/hole plane
(d) peg chamfer edge/hole wall*
(e) peg wall/hole edge
(f) peg chamfer face/hole edge

(iii) Plane/plane contact; (a) peg face/hole plane
(b) peg chamfer face/hole plane
(c) peg chamfer face/hole wall*
(d) peg wall face/hole wall.

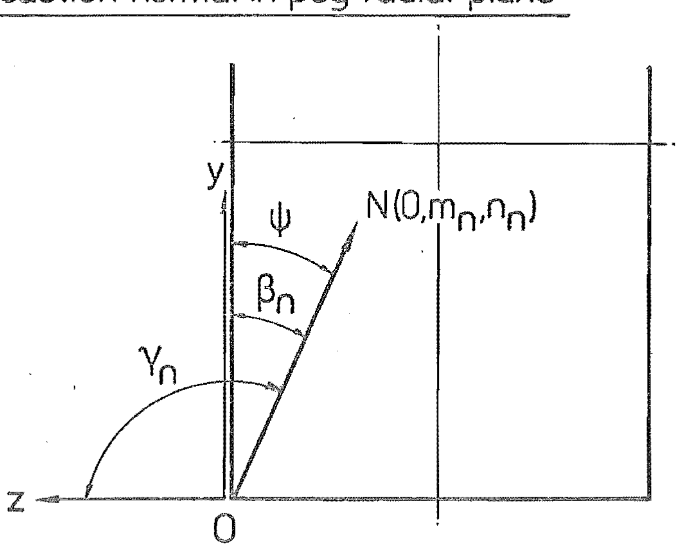
*implies that this mode of contact is possible only in certain geometrical conditions.

FIG.7.5 PEG-HOLE LINE/LINE CONTACT

(a) Peg edge/hole edge contact



(b) Reaction normal in peg radial plane



The three primary types of contact will now be investigated with regard to the direction of the contact normal.

7.4 Line/Line Contact

Figure 7.5(a) represents a peg edge in contact with a hole perimeter. $\vec{OC}$ is the direction of the peg-edge and $\vec{OH}$ that of the hole. Relative to the x-y-z co-ordinate system fixed to the peg, the direction cosines are :-

$$\vec{OC} \;;\quad (\ell_c, m_c, n_c) \;=\; (1,\ 0,\ 0)$$

$$\vec{OH} \;;\quad (\ell_h, m_h, n_h) \;=\; (\cos\alpha_h,\ \cos\beta_h,\ \cos\gamma_h).$$

Now, it is assumed that the normal reaction direction, in line/line contacts, is parallel to the normal of the plane containing the two lines. Let the direction cosines of the contact normal, $\vec{ON}$, be (ℓ_n, m_n, n_n) and therefore taking the dot product :

$$\ell_n.\ell_h + m_n.m_h + n_n.n_h \;=\; 0$$

and $\ell_n.\ell_c + m_n.m_c + n_n.n_c = \ell_h.1 = 0$

$$\therefore \quad m_n.m_h \;=\; -n_n.n_h$$

$$\text{i.e.} \quad \frac{m_n}{n_n} \;=\; -\frac{n_h}{m_h} \tag{7.6}$$

$\therefore$ the direction cosine of $\vec{ON}$ is :

$$\left[\ 0,\ \frac{n_h}{\sqrt{n_h^{\,2} + m_h^{\,2}}},\ \frac{-m_h}{\sqrt{n_h^{\,2} + m_h^{\,2}}}\ \right] \tag{7.7}$$

From this it is seen that $\vec{ON}$, the reaction normal, lies in the radial plane of the peg.

Consider this radial plane, shown in Figure 7.5(b). Let the angle of the reaction normal, $\vec{ON}$, to the peg axis be ψ, then $\psi = \beta_n$, hence $m_n = \cos\beta_n = \cos\psi$, and :

$$n_n = \cos\gamma_n = \cos(\frac{\pi}{2} + \psi).$$

Substitution of these values in Equation (7.6) gives :

$$\frac{\cos\psi}{\cos(\frac{\pi}{2} + \psi)} = \frac{\cos\psi}{-\sin\psi} = \frac{n_h}{-m_h}$$

$$\text{i.e. } \tan\psi = \frac{m_h}{n_h} = \frac{\cos\beta_h}{\cos\gamma_h} \tag{7.8}$$

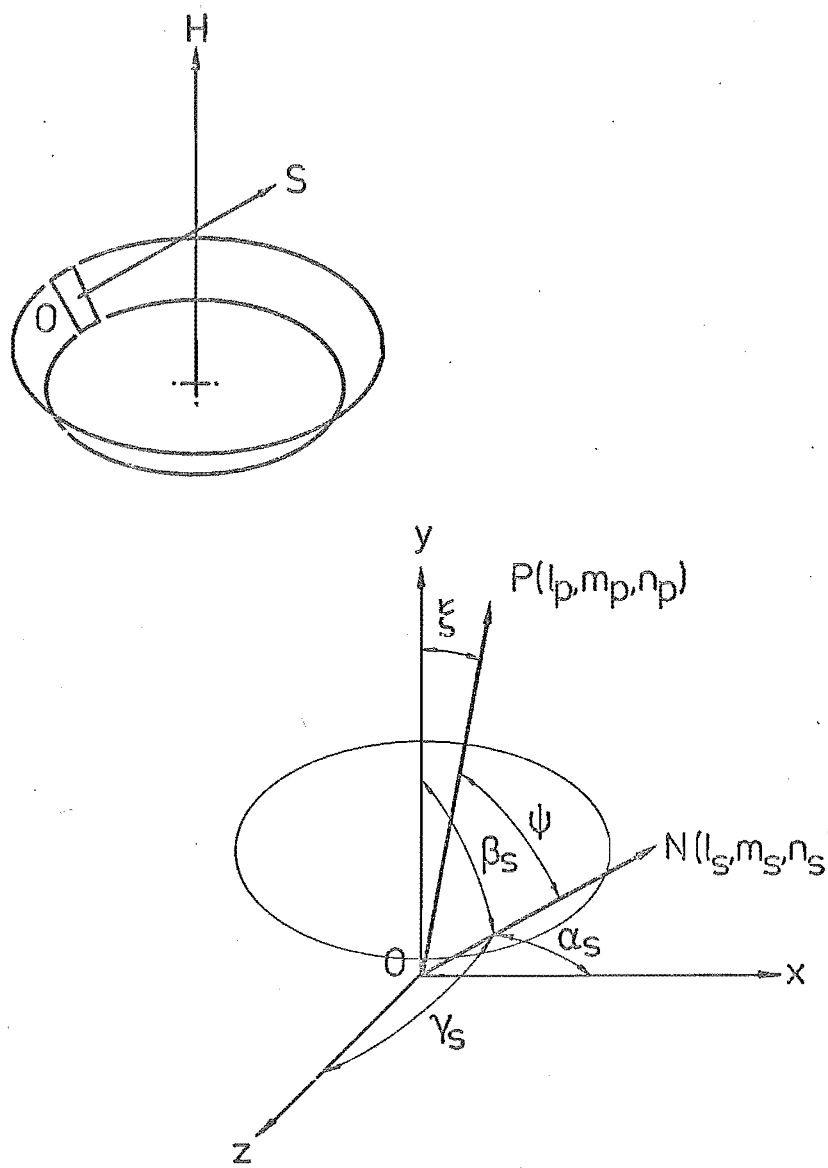
Note that the angle ψ is dependent only on the relative alignment of $\vec{OC}$, to $\vec{OH}$, and that $\vec{OH}$ (which is a line segment of the hole perimeter) does not specify the gross orientation of the hole. Hence measuring the directions of the resultant forces and moments on the peg will not completely define the orientation of the peg with respect to the hole. This will be further discussed in Chapter 8.

7.5 Line/Plane Contact

Line/plane contacts are divisible into two categories on the criterion of effect on a sensing peg. If the contact is peg line/plane, then the direction of the contact normal as sensed by the peg, is dependent on the orientation of the plane and the relative alignment of the peg. If, on the other hand, the contact is peg plane/line, then the contact normal direction depends only on the geometry of the peg. This second condition is analagous to plane/plane contacts.

The first condition may occur when an edge of one of the elemental planes of a peg contacts a surface such as a hole plane or a chamfer plane. The reaction is taken through this line contact and is parallel to the normal to the plane surface. Since this reaction is also normal to the contacting line it lies in a radial plane of the peg. Therefore, the angle ψ (between the contact normal, $\vec{ON}$, and the peg axis) is the angle between the normal to the plane at the contact $\vec{OS}$, and the peg axis. Figure 7.6.

FIG.7.6 PEG EDGE/CHAMFER PLANE CONTACT



To calculate ψ in the case of contact with a chamfer, consider Figure 7.6 which shows an elemental chamfer plane whose direction is defined by its surface normal $\vec{OS}$. In the reference frame x, y, z where $\vec{Oy}$ is aligned to the hole axis $\vec{H}$, the vector $\vec{OS}$ has direction cosines (ℓ_s, m_s, n_s); the angle β_s and thus the direction cosine m_s is a constant when the chamfer is symmetrical. If the peg axis, $\vec{OP}$, is now defined by (ℓ_p, m_p, n_p), the angle ψ is given by:

$$\cos\psi = \ell_p.\ell_s + m_p.m_s + n_p.n_s \qquad (7.9)$$

Let the peg misalignment be given as an angle ξ, between the directions $\vec{Oy}$ and $\vec{OP}$. Arbitrarily letting $\vec{OP}$ lie in the xy plane :

$$(\ell_p, m_p, n_p) \text{ becomes } (\cos(\tfrac{\pi}{2}-\xi),\ \cos\xi, 0)$$

and if the particular chamfer normal is (ℓ_s, m_s, n_s).
i.e. $(\cos\alpha_s, \cos\beta_s, \cos\gamma_s)$, Equation (7.9) becomes :

$$\cos\psi = \cos(\tfrac{\pi}{2} - \xi).\cos\alpha_s + \cos\xi.\cos\beta_s \qquad (7.10)$$

the only variable being α_s, which lies in the range

$$\frac{\pi}{2} - \beta_s \leqslant \alpha_s \leqslant \frac{\pi}{2} + \beta_s.$$

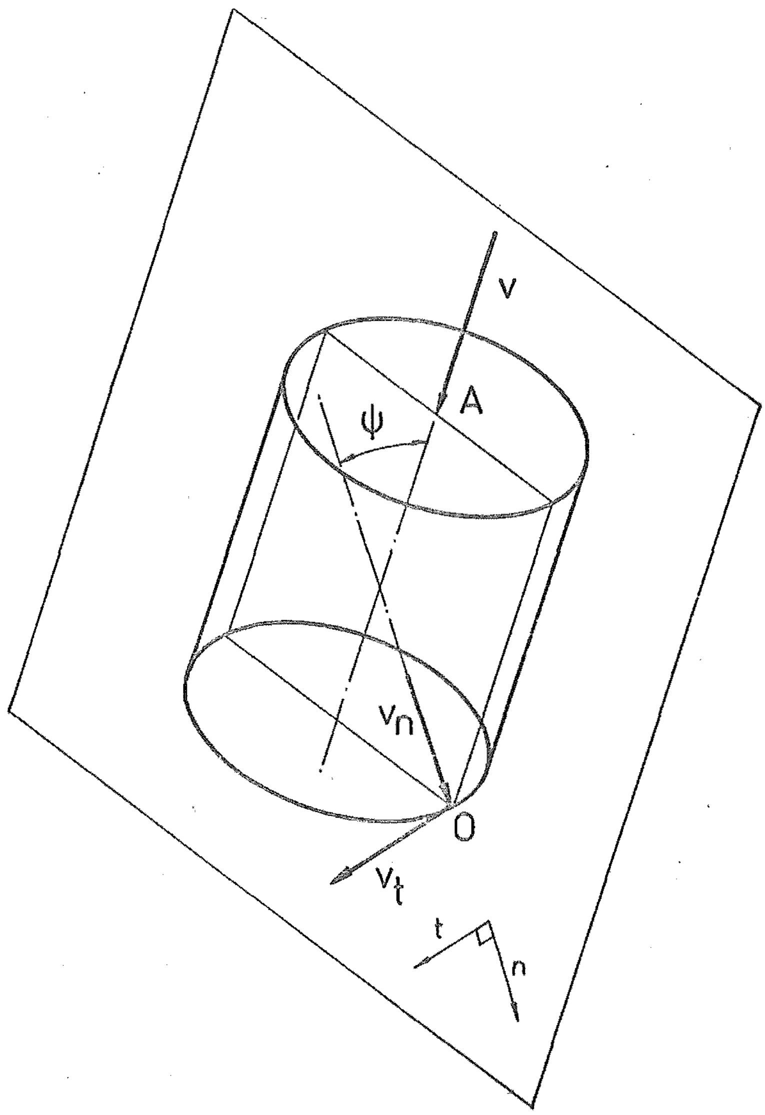
Thus, the limits of ψ may be found, but again it is seen that a particular peg misalignment (ξ angular misalignment) does not correspond to a unique reaction normal direction. Further consideration of this aspect with regard to tactile feedback appears in Chapter 8.

Similarly Equation (7.9) may be used to establish the ψ value of any other line/plane contact where (ℓ_p, m_p, n_p) and (ℓ_s, m_s, n_s) are the peg axis and plane normal directional cosines respectively.

7.6 Plane/plane Contact

When two planes contact, the reaction normal is, of course, directed along the common direction of the normals to the contacting surfaces.

FIG.7.7 BODY IMPACTS



The angle ψ is fixed by the geometry of the peg, and again $\vec{ON}$ lies in a radial plane of the peg. As the reaction normal direction is solely dependent on the peg geometry, the unique relationship sought between misalignment and contact normal direction does not exist.

Now that the types of contacts possible with a peg and a hole are defined, and the direction of the reaction normal derived, the possibility of using body contacts as either a medium for tactile sensing or the mechanism of a self-aligning interaction system, can be investigated.

7.7 Contact Impacts

The preceding sections investigated the contact reaction force direction resulting from the various forms of body interactions. Also of importance, is the behaviour of a system when that contact is subjected to impact; that is, when the bodies contact with a non-zero relative velocity.

Consider Figure 7.7 in which a peg with velocity v in its longitudinal direction makes contact with another body at a point O. At this contact point, the pre-impact velocity is resolvable into components in the contact normal direction $\vec{n}$, and a contact tangential direction, $\vec{t}$, i.e. vectorially :

$$v = v_n + v_t \tag{7.11}$$

The $\vec{n}$ and $\vec{t}$ directions are related to the peg axial line by the angle ψ discussed previously for the various contact forms. So:

$$\begin{aligned} v_n &= v\cos\psi \\ v_t &= v\sin\psi \end{aligned} \tag{7.12}$$

Depending on the elasticity of the bodies and the frictional coefficient at the impact point, the post-impact velocities v_n' and v_t', along the given directions are :

$$v_n' = \alpha v_n \qquad -1 \leqslant \alpha \leqslant 0$$
$$v_t' = \beta v_t \qquad -1 \leqslant \beta \leqslant 1 \tag{7.13}$$

The range of values of α and β are now discussed :-

$\alpha = 0$; when impact is totally plastic

$\alpha = -1$; when impact is totally elastic

$\beta = -1$; when impact is totally elastic <u>and</u> $\mu = \infty$ (7.14)

$\beta = 0$; when impact is totally plastic <u>and</u> $\mu = \infty$

$\beta = 1$; when $\mu = 0$.

Therefore, the impulses at 0, on the peg, are :

$$I_n = m(v_n' - v_n) = m\, v\cos\psi\ (\alpha - 1)$$
$$I_t = m(v_t' - v_t) = mv\sin\psi\ (\beta - 1) \tag{7.15}$$

where m is the mass of the dynamic system.

The rotatory impulse, I_w, about A is

$$I_w \text{ @ } A = -I_n\cos\psi C_x + I_n\sin\psi 2C_y - I_t\sin\psi C_x - I_t\cos\psi 2C_y$$
$$= I_n(\sin\psi 2C_y - \cos\psi C_x) - I_t(\sin\psi C_x + \cos\psi 2C_y) \tag{7.16}$$

where C_x and C_y relate to the peg geometry.

These then are the contact impulses acting on the peg system. The resulting behaviour, of course, is dependent on the mode of manipulation of the peg.

CHAPTER EIGHT

SIMPLE TACTILE FEEDBACK

8.1 Introduction

In Chapter 7 the behaviour of a peg in contact with a hole was analysed. The resulting reaction force was related to the forcing effort, the contact geometry, and the friction at the contact point. It was felt that if this reaction force has a property that is a function of the peg/hole misalignment, then perhaps it could be used for sensing that misalignment.

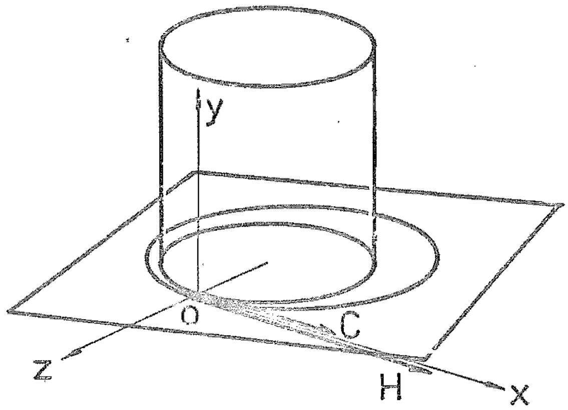
Ideally, a sensed property, or manifestation of the reaction force, corresponds to the misalignment and is independent of the contact form. If this could be found, then an inexpensive and reliable solution to placement Phase I would be made available.

The reaction force was found to be inextricably tied up with the contact reaction normal. This reaction normal is dependent on the contact geometry. Because a diverse range of contact forms is available for the peg-hole assembly (Chapter 7, Section 3), there will also be a diverse range of reaction force directions possible for any particular peg-hole misalignment. These will be investigated in an attempt to find a cohesive pattern through which misalignment can be unambiguously related to some facet of the reaction force.

Firstly, the various contact forms will be re-examined to derive the range or spread of the sensed property, and secondly, these forms will be gathered into a full peg-hole situation. Then an attempt will be made to derive a common property through which misalignment can be sensed irrespective of which particular form contact happens to take.

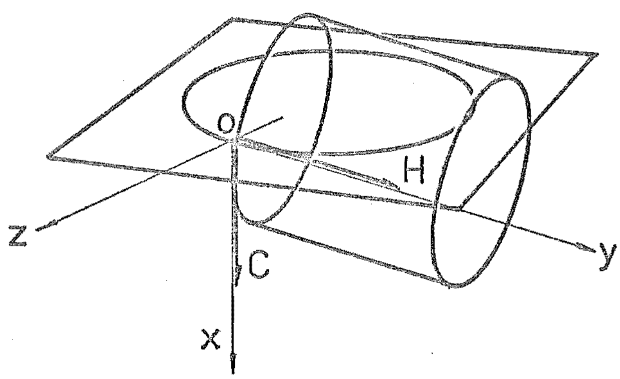
FIG. 8.1 SALIENT LINE/LINE CONTACTS

(a)



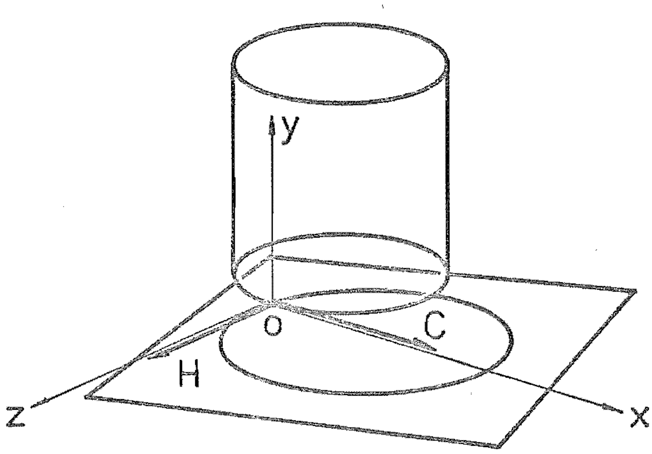
$\vec{OH} = (1,0,0)$
ψ = indeterminate

(b)



$\vec{OH} = (0,1,0)$
$\psi = \pi/2$

(c)



$\vec{OH} = (0,0,1)$
$\psi = 0$

FIG. 8.2 TYPICAL LINE/LINE CONTACT

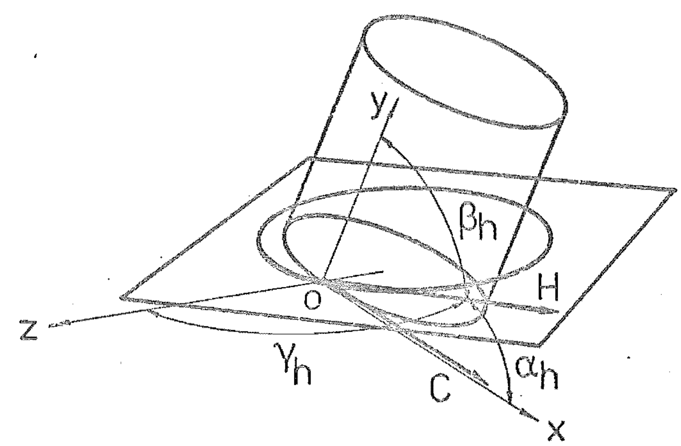
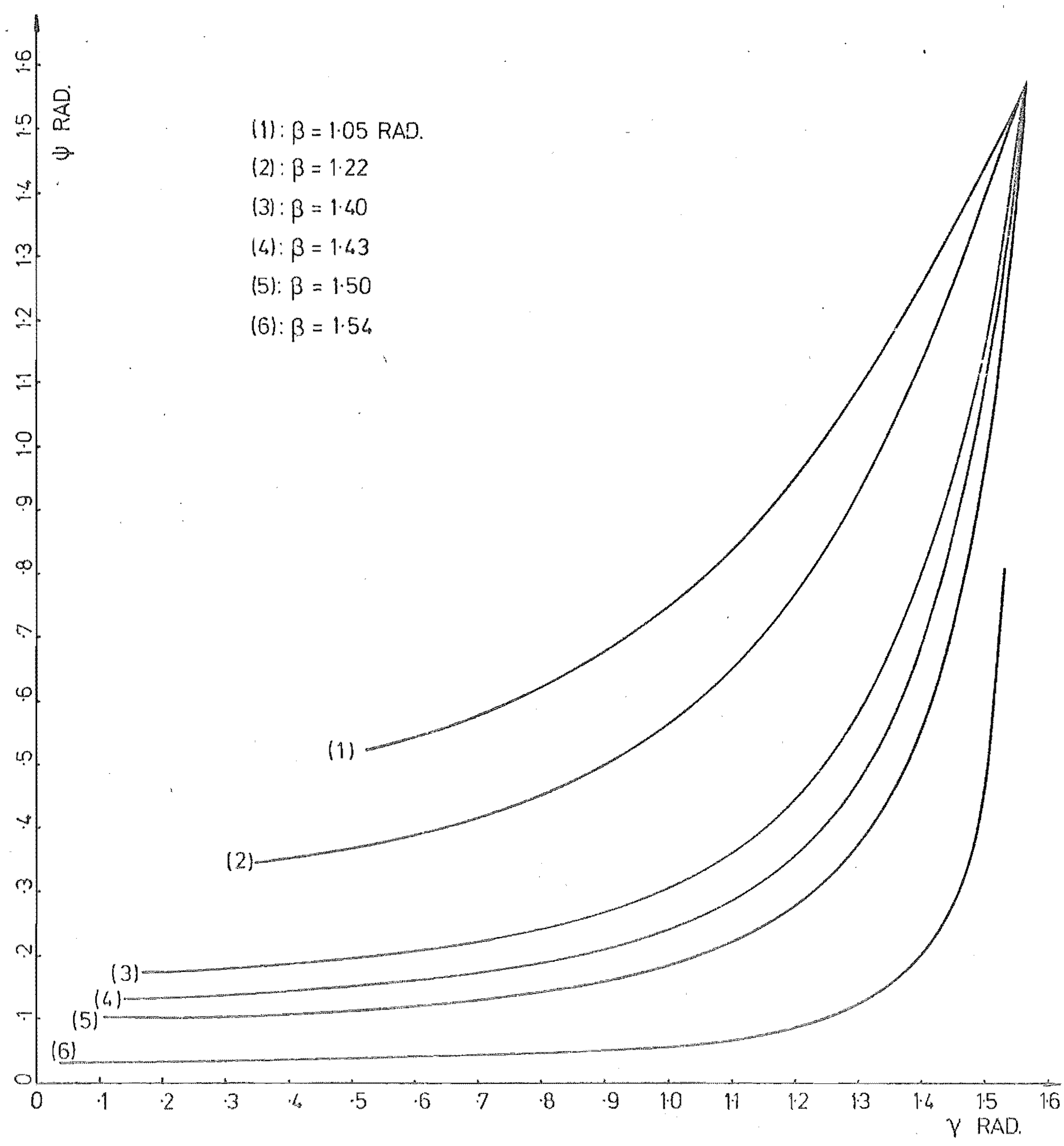


FIG. 8.3 LINE/LINE CONTACT: ψ, γ, β VARIATIONS



8.2 Line/Line Contact

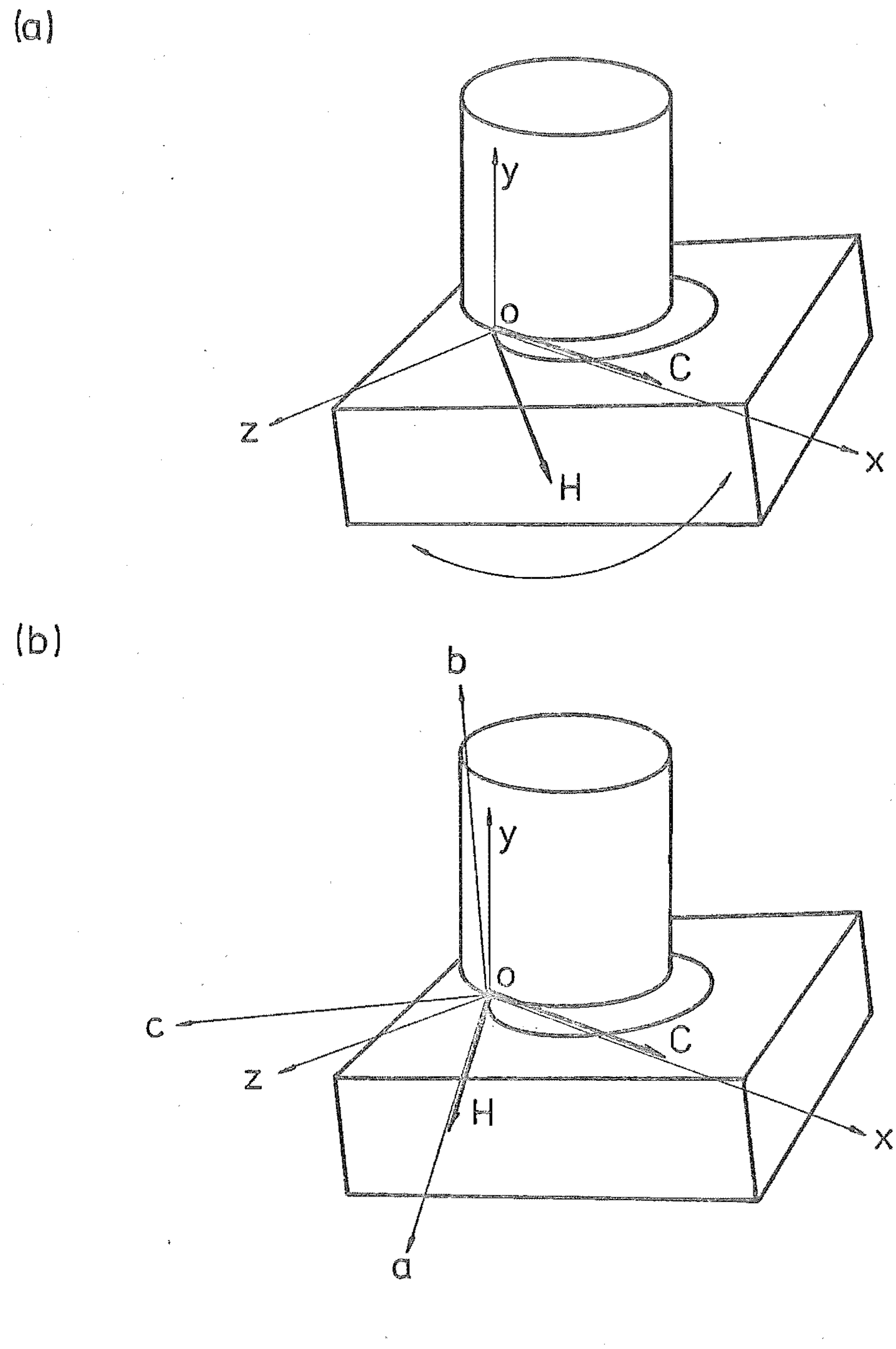
For line/line contacts, the expression derived in Chapter 7 to relate the reaction normal direction, as felt by the peg, to the angle between the intersecting peg and hole edges is Equation (7.8)

$$\tan\psi = \frac{m_h}{n_h} = \frac{\cos\beta_h}{\cos\gamma_h} \tag{8.1}$$

ψ is the angle between the reaction normal, $\vec{ON}$, and the peg axis directions, and (ℓ_h, m_h, n_h) is the directional cosine of the contact line element direction $\vec{OH}$ of the hole with regard to the peg. (See Figures 7.5(a) and (b)). The range of possible ψ values due to the variation of $\vec{OH}$ direction will be investigated now. In Figure 7.5(a), $\vec{OC}$ is the peg line segment direction; $\vec{OH}$ is the hole line segment direction, and it is the relative angle between these that determines ψ. Figure 8.1 shows some salient relative directions of these, where $\vec{OH}$ is aligned to each of the x, y and z axes. These are extreme and pure contact forms, and because of interfering geometry, and the fact that in real situations parallel line/line contacts are not readily achieved, some forms (Figure 8.1(a) and (b)) are not found in practice. The ψ values for these extremes are shown, for real situations which are combinations of various degrees of these illustrated pure forms, the ψ values fall between 0 and $\pi/2$. Figure 8.2 shows a typical peg-hole line/line contact situation and for these, Figure 8.3 shows graphically, the relationship between ψ, β_h and γ_h, that is, Equation (8.1).

The above analysis is for the reaction normal direction due to the contact of a peg line segment $\vec{OC}$, and a hole line segment $\vec{OH}$, referred to the peg's co-ordinate system. Since $\vec{OH}$ is the direction of a line segment on the circumference of a hole it cannot completely define the hole position. The hole can still rotate about this vector, $\vec{OH}$.

FIG. 8.4 WHOLE BODY ORIENTATION OF THE PEG AND HOLE



(see Figure 8.4(a)). To define the orientation of the hole with respect to the peg completely, an additional angle, say $b\hat{O}y$ – that between the peg and hole axes, will have to be specified, Figure 8.4(b). The factors limiting the size of $b\hat{O}y$ are physical; that is, arising from physical interference between the peg and the hole, or the hole plane.

The angle ψ, that is the reaction normal as sensed by the peg, is independent of the angle $b\hat{O}y$ and therefore ψ is not singly related to the angular misalignment between the peg and the hole axes. So, monitoring the angle ψ does not give the absolute angular misalignment of the peg and hole axes.

8.3 Line/Plane Contact

For line/plane contacts, it was found that whether a peg sensed reaction was dependent on misalignment depended on the type of line/plane contact. A peg-line/plane contact reaction normal is sensitive to peg axis direction variations, whereas a peg-plane/line contact is not.

The two types of line/plane contacts will be examined with regard to usefulness as tactile sensing mediums.

(1) Peg-line/plane Contact

Section 7.5 established that for peg-line/plane contacts, the reaction normal direction as referred to the peg lies in a radial plane of the peg and makes an angle ψ with regard to the peg axis, where ψ is given by Equation (7.9).

$$\cos\psi = \ell_p.\ell_s + m_p.m_s + n_p.n_s \tag{8.2}$$

(ℓ_p,m_p,n_p) and (ℓ_s,m_s,n_s) are the direction cosines of the peg, and the normal of the contact plane, respectively. Consideration will now be given to the various types of peg-line/plane contacts.

(a) Peg-line/Hole plane contact.

Figure 8.5 shows a peg in contact with the hole plane. As illustrated, $(\ell_s, m_s, n_s) = (0,1,0)$, such that Equation (8.2) becomes :

$\cos\psi = m_p$, i.e. $\psi = \beta_p$.

For this type of contact, β_p is equal to the angular misalignment, ξ, between the peg and the hole plane normal. Therefore, $\vec{ON}$ lies in the plane of maximum angular misalignment (ξ), and its direction with regard to the peg axis, ψ, is directly related to ξ,

i.e. $\beta_p = \xi = \psi$ (8.3)

This is the case of a one-to-one correspondence between the reaction normal direction (on which the resultant reaction direction is based) as felt by the peg, and the peg misalignment.

(b) Peg-line/Chamfer Face Contact.

For this case; contact between the peg edge and chamfer face, the expression for the angle ψ is given by Equation (7.10) -

$$\cos\psi = \cos\left(\frac{\pi}{2} - \xi\right).\cos\alpha_s + \cos\xi.\cos\beta_s \qquad (8.4)$$

ξ is the angular misalignment between the peg and the hole axes; $(\cos\alpha, \cos\beta, \cos\gamma)$, i.e. (ℓ_s, m_s, n_s), is the dir. cosine of the normal to the particular chamfer plane segment in contact. The chamfer being axisymmetrical, implies m_s (and therefore β_s) constant, so α_s is the only variable, lying in the range :

$$\frac{\pi}{2} - \beta_s \leqslant \alpha_s \leqslant \frac{\pi}{2} + \beta_s \qquad (8.5)$$

Substitution of the limits expressed in Equation (8.5) into Equation (8.4) reveals that ψ is bounded so :

$$\beta_s - \xi \leqslant \psi \leqslant \beta_s + \xi \qquad (8.6)$$

If a typical chamfer angle is 45° ($\beta_s = 45^\circ$), and the allowable angular misalignment is, say, 15°, then ψ varies between 30°

FIG. 8.5 PEG EDGE/HOLE PLANE CONTACT

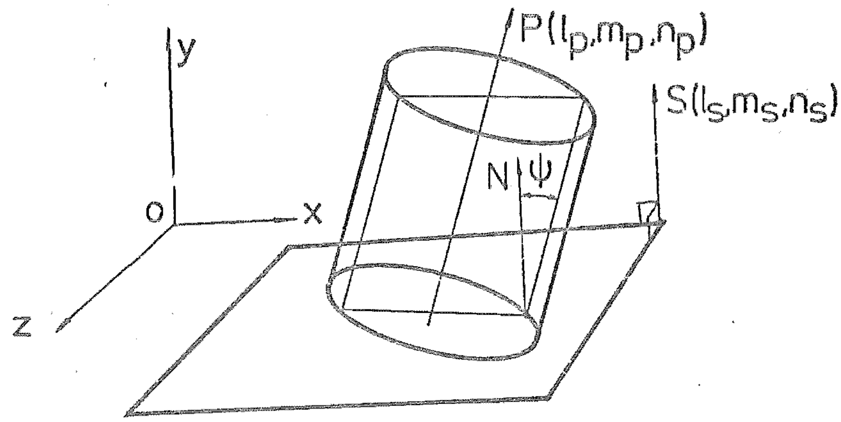


FIG. 8.6 PEG EDGE/HOLE CHAMFER FACE CONTACT

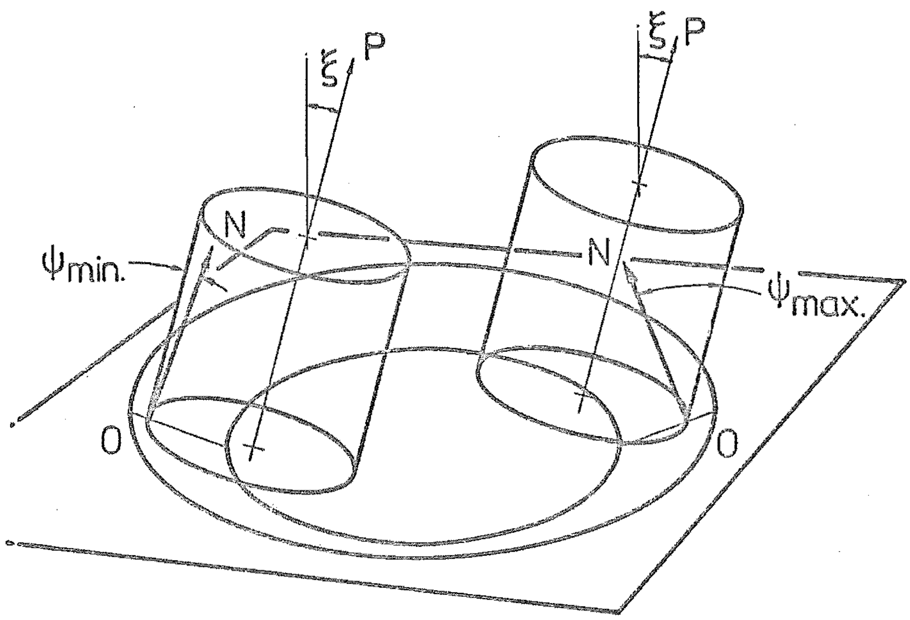
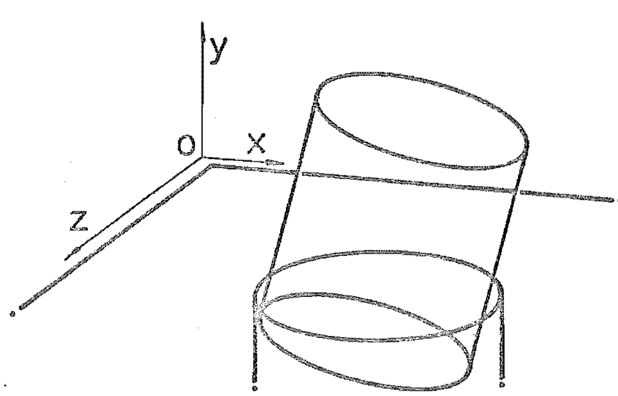


FIG. 8.7 PEG EDGE/HOLE WALL CONTACT



and 60° for a constant angular misalignment, depending on the position on the chamfer the contact is made. Also, $\vec{ON}$ does not necessarily lie in the plane of maximum misalignment, see Figure 8.6. Certainly, a particular misalignment of the peg and hole does not correspond to a unique sensed reaction dir.

(c) Peg-line/Hole wall contact.

Figure 8.7 illustrates this line/plane contact case, $\vec{OS}$ now being the direction of an element on the hole wall and becomes $(\ell_s, 0, n_s)$ with regard to the shown co-ordinate axes. Equation (8.2) therefore transforms to :

$$\text{Cos}\psi = \ell_p . \ell_s + n_p . n_s \qquad (8.7)$$

Again, obviously ψ does not always lie in the plane of maximum angular misalignment.

(2) Peg-plane/Line Contact

For peg-plane/line (or equivalent) contacts, the reaction normal direction (and thus the resultant reaction direction) as sensed by the peg, is dependent only on the peg geometry. An equivalent peg/plane line contact is one in which there are two simultaneous line/line contacts, like overlapping perimeters, resulting in plane/line behaviour.

For these contacts, the reaction normal lies on a radial plane of the peg and acts at the contact point in a direction parallel to the normal, $\vec{OS}$, of the contacted peg-plane. Therefore, ψ is again given by :

$$\cos\psi = \ell_p . \ell_s + m_p . m_s + n_p . n_s \qquad (8.2)$$

However, since for an axisymmetrical peg this plane has a constant relation to the peg axis, ψ = constant, say :

$$\psi = \rho \qquad (8.8)$$

where ρ is the angle between the normal of the contacted peg-plane and the peg axis.

FIG. 8.8 PEG-PLANE/LINE CONTACT

(a) $\rho = \pi/2 = \psi$

(b) $\rho = \pi/2 - \phi = \psi$

ϕ = chamfer angle

(c) $\rho = 0 = \psi$

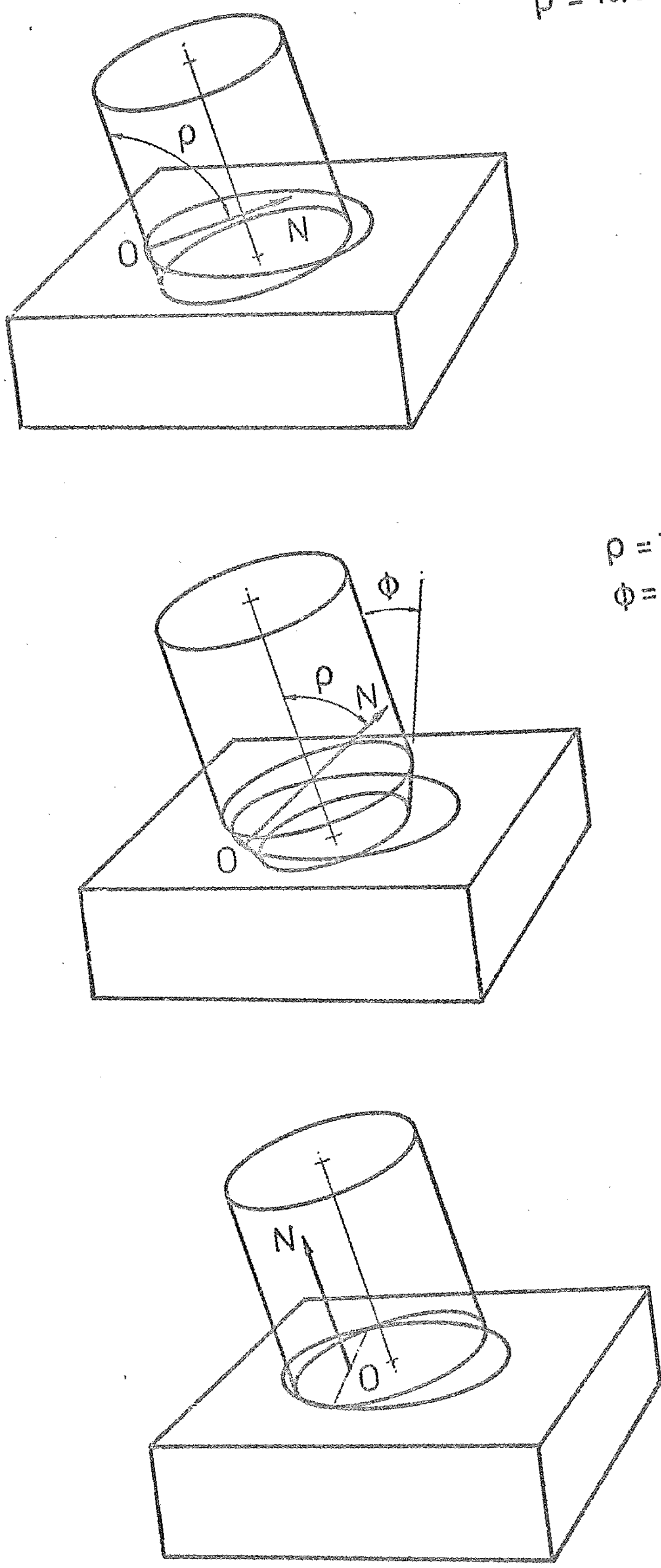


Figure 8.8(a), (b) and (c) shows the three cases of peg-plane/line contact:

(a) peg wall/hole edge;

(b) peg chamfer face/hole edge;

(c) double peg edge/hole edge contacts; i.e. equivalent peg-plane/line.

So for these, as the peg is rotated about the contact point(s), so altering the misalignment, ψ remains constant. Therefore, the resultant reaction, R, which is related to $\vec{ON}$ by the cone of friction is perceived to be stationary, thus giving no indication of the state of peg-hole alignment.

8.4 Plane/Plane Contact

Dissimilar to the peg-plane/line category of contacts, if plane/plane contact is established with the prior knowledge that it is plane/plane, then the state of alignment can be derived. However, there is no way of indicating that a contact is plane/plane or peg-plane/line by a single contact.

The contact normal, $\vec{ON}$, lies in a radial plane of the peg, and acts in a direction parallel to the normal of the peg face, the peg chamfer face, or the peg wall, whichever is contacted. Respectively, the angle $\psi(= \rho)$ is equal to 0, $\frac{\pi}{2} - \phi_p$, or $\frac{\pi}{2}$, where ϕ_p is the peg chamfer angle.

8.5 Tactile Sensing

Now that the knowledge of the behaviour of the contact force in each of the line/line, line/plane, and plane/plane contact forms have been expanded, they can be combined to form sets of possible contact forms that may arise for each of the various peg-hole combinations. A consistent tactual property in these combinations will be sought to measure misalignment.

For obvious reasons, it is more desirable to measure the reaction force through the peg than through the hole. If the peg is gripped in the manipulating hand containing the sensors, then the contact forces and moments can be directly related to the geometry of the peg. If the contact forces on the hole are measured, the readings are modified by the intervening geometry between the measuring points and the hole. This could be further complicated by variations of the intervening geometry as assembly progresses, and by any 'slop' in the aggregate system due to the build-up of clearances, etc. between the controlled and measurement points. Therefore, force and moment effects will be viewed in the light of their relationship to the peg.

For practical reasons relating to the ease of control, it is desirable to sense stationary alignment states. The necessary conditions for a stationary contact state were discussed in Section 7.2. Primarily, the stationary peg system experiences no body forces or moments, and the sums of the forces, and moments, on the system are both zero. If necessary, the force balance is achieved by the rearrangement of the force and moment acting through the manipulator/system interface. Figure 8.9 illustrates a range of stationary peg/plane contacts at various angular misalignments (ξ). The direction of the reaction force (R) is determined by the contact form (line/plane) and cannot deviate outside the cone of friction (semi angle α_f) aligned on $\vec{ON}$. Thus, sensed at A (see Figure 8.9 (e)) respectively for cases

(a) $\xi < \alpha_f$; $F_v = P$, $F_w = 0$, $M_\theta = P.C_x$ (8.9)

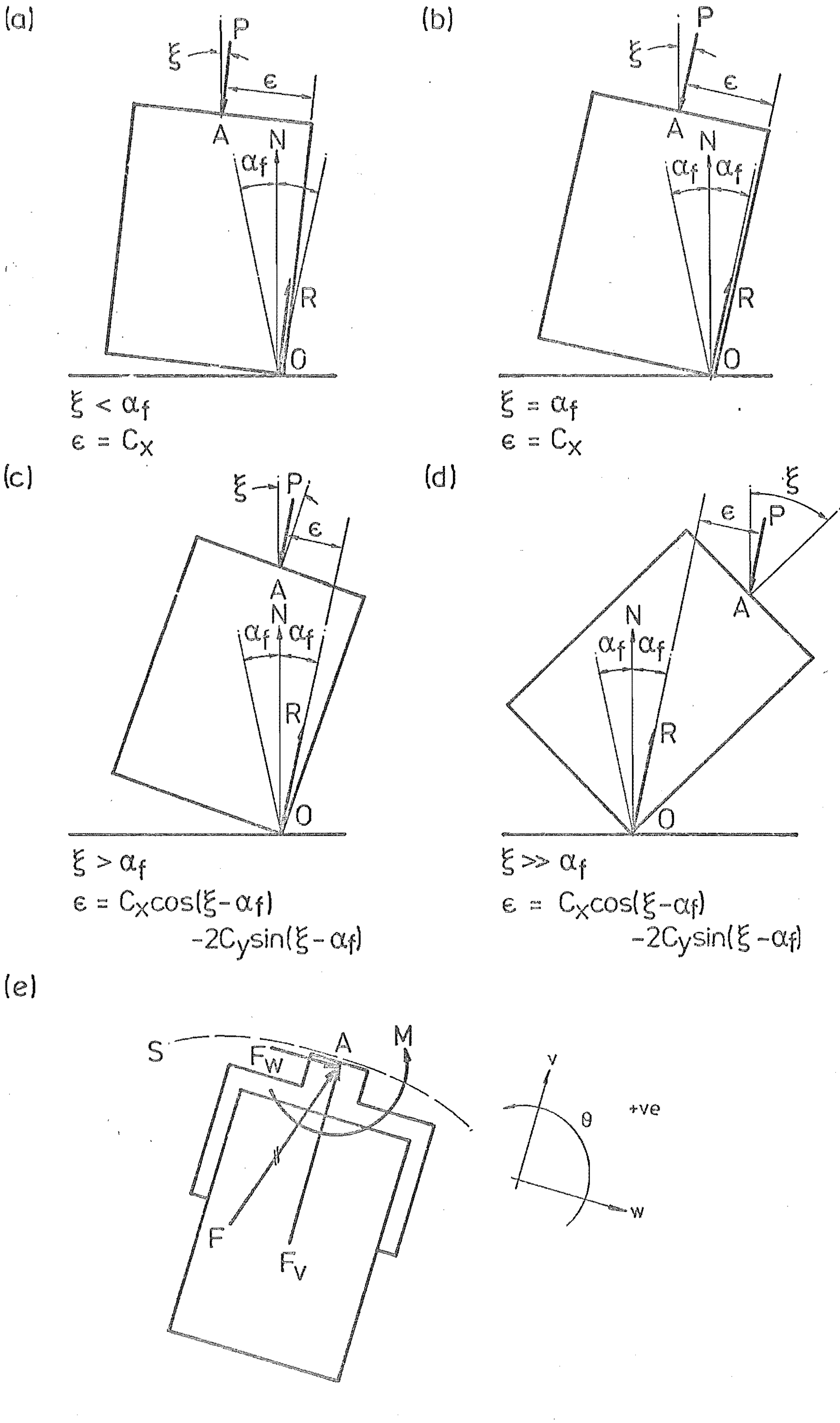
(b) $\xi = \alpha_f$; $F_v = P$, $F_w = 0$, $M_\theta = P.C_x$ (8.10)

(c) and (d) $\xi > \alpha_f$; $F_v = P\cos(\xi - \alpha_f)$

$$F_w = -P\sin(\xi - \alpha_f)$$

$$M_\theta = P(C_x\cos(\xi - \alpha_f) - 2C_y\sin(\xi - \alpha_f)) \quad (8.11)$$

FIG. 8.9 PEG/HOLE PLANE CONTACT FORCES AND MOMENTS



Note that as ξ increases, a point (dependent of the peg geometry C_x and C_y) is reached where M_θ reverses direction. Specifically, this occurs when

$$\xi = \alpha_f + \tan^{-1} (C_x/2C_y) \tag{8.12}$$

Now the various peg-hole combinations will be analysed with regard to the types of contact forms possible to see if any sensed property of the contact force has a consistent relationship to misalignment. The various peg-hole combinations and their possible contact forms have already been documented in Section 7.3. Briefly, these combinations are :

(i) Unchamfered peg - unchamfered hole

(ii) Unchamfered peg - chamfered hole

(iii) Chamfered peg - chamfered hole

(iv) Chamfered peg - unchamfered hole.

(i) Unchamfered Peg - Unchamfered Hole

In section 7.3, subsection 1, is documented the types of contact forms likely to be encountered in assembling this combination.

For line/line contacts of the peg-edge/hole edge type, section 8.2 examined the range of contact normal directions and their relationship to the plane of maximum angular misalignment. In general, for line/line contacts, the reaction normal $\vec{ON}$ lies in the radial plane of the peg that contains the contact point 0, and $\vec{ON}$ has ψ values between 0 and $\pi/2$. See Figure 8.10. Sensed at A, is a direct force, a shear force, and a tipping moment due to R.

Consider measuring the direction of R; its direction bears no direct relationship to the peg-hole (ξ) misalignment, but

FIG. 8.10 LOCUS OF REACTION FORCE ON MOTION CONSTRAINED PEG

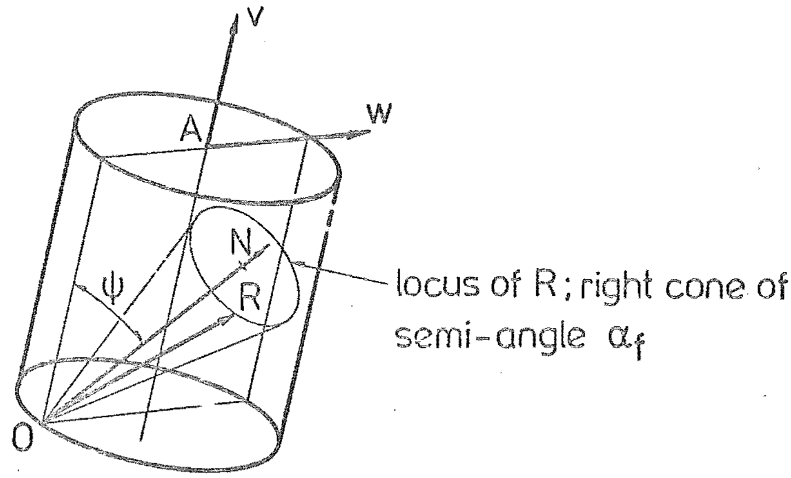
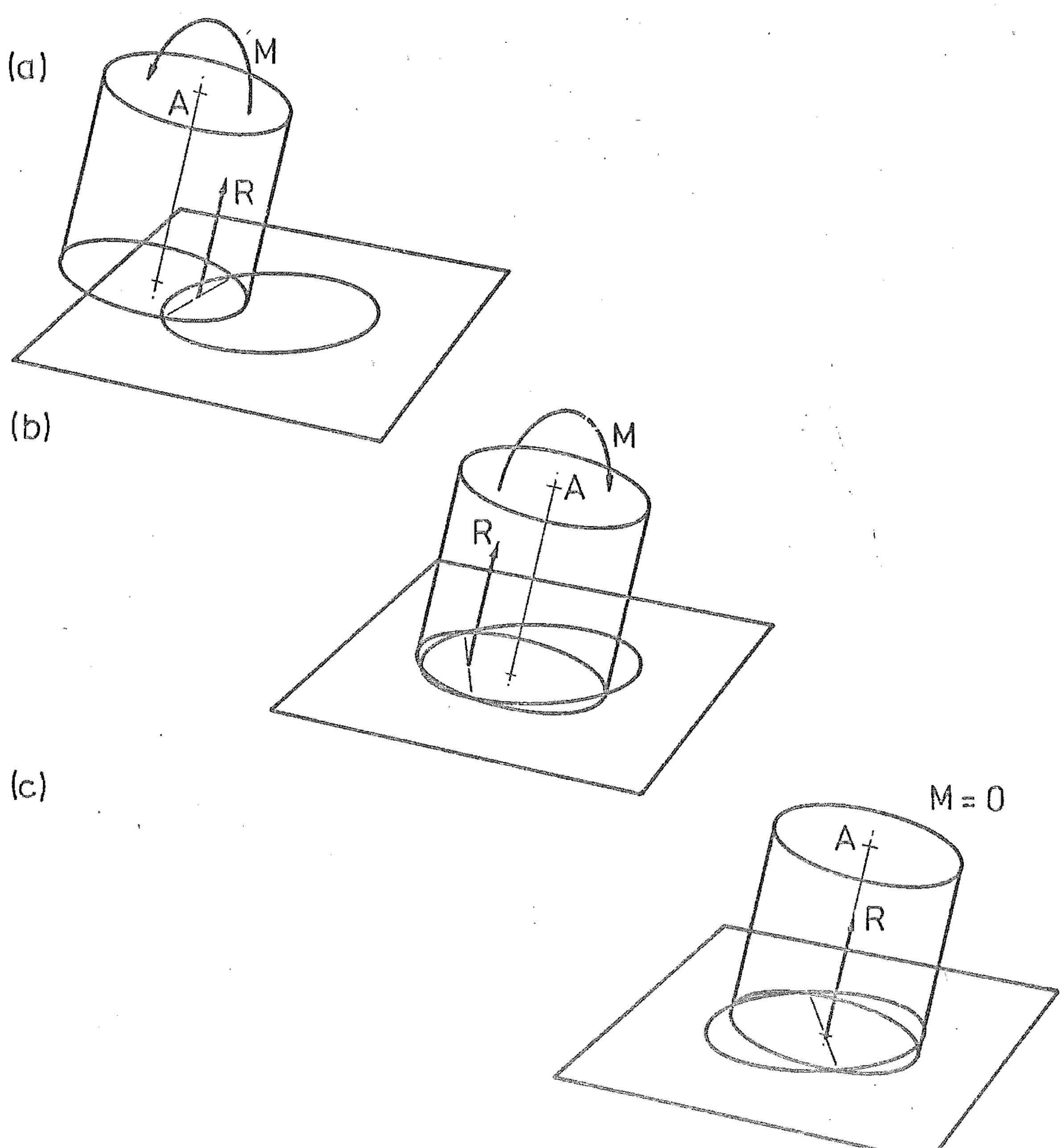


FIG. 8.11 VARIOUS PEG-FACE/HOLE LINE CONTACTS



pertains more to the angle of $\vec{OC}$, $\vec{OH}$ contact. If line/line contact was the only contact form of concern, then perhaps an indirect relationship between ξ and the R direction may be derivable; however, since line/plane and plane/plane contacts are just as likely to occur, then any specific relationship correct for one contact form is not applicable to the other two. If the measurement of R does not promise a simple tactile solution, perhaps the more general property of "general-dir.-of-R" will provide a workable basis. This shall be investigated.

If the peg is, say, rotated in the direction of the sensed shear force, then either :

(1) a peg base plane/hole plane contact, or

(2) two simultaneous peg edge/hole edge contacts are made.

If (1) is the case, then an alignment of the peg and hole axes directions is achieved. If the latter occurs, then the contact form changes to one of peg-face/line contact; section 8.3(2).

In a peg face/line contact, only a direct force and a moment is felt at A. Figure 8.11 shows three possible peg face/line contacts. All three cases show the same misalignment, but the sensed moment (the only tactually sensible difference), is different for each case. On this account, to react in a fixed manner to the sensed moment would in case (a) improve alignment, and in case (b) worsen it. One solution (referred to later) is to make the situations (b) and (c) impossible by increasing the peg's diameter beyond that of the hole's.

The peg edge/hole plane contacts are described in the previous section and illustrated in Figure 8.9. Here, the force and moment plane coincides with the plane containing the maximum angular misalignment (ξ). So the strategies of

(a) rotation in the direction of the sensed shear force; and

(b) rotation in the direction of the sensed moment when no shear force exists

will achieve alignment of the peg and hole axes.

For the case of peg wall/hole edge contact the former of the above strategies will achieve similar results.

The case of peg edge/hole wall contact will not occur in practice unless the clearance between the peg and the hole is large, and the assembly system possesses extreme stiffness.

So it seems that apart from one ambiguity (of likely occurrence) associated with the event of peg face/line contacts the general strategies of

(a) Rotation in the direction of the sensed shear force; and

(b) Rotation in the direction of the sensed moment <u>when no shear force exists</u> (8.13)

will align the peg and hole axes.

(ii) <u>Unchamfered Peg - Chamfered Hole</u>

Peg edge/line contacts in this combination arise from two areas, one in contact with the hole edge, and two, in contact with the hole chamfer edge. Because in the second case the contact perimeter is considerably larger in diameter than that of the peg

FIG. 8.12 PEG EDGE / HOLE CHAMFER FACE CONTACT

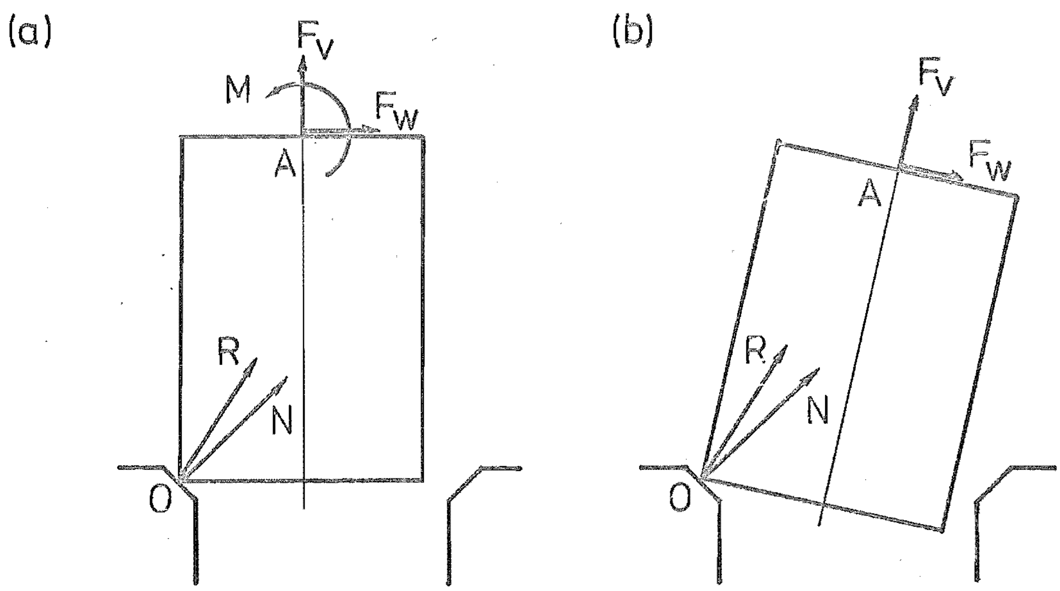
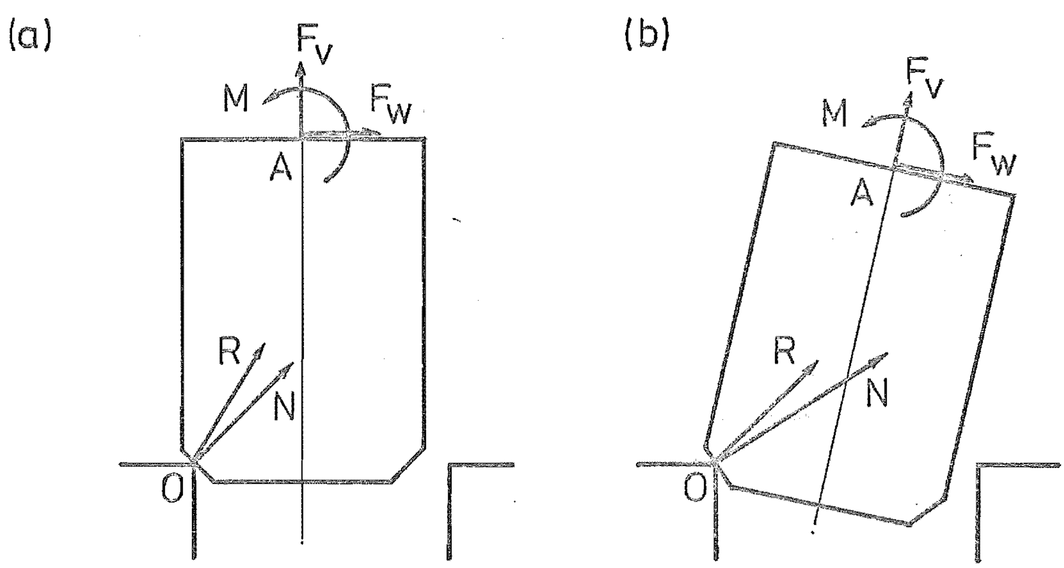


FIG. 8.13 PEG CHAMFER FACE / HOLE EDGE CONTACT



edge, the chance of resulting in a situation illustrated in Figure 8.11 is greatly enhanced. Thus strategy (8.13) is inadequate for this contact form.

The general strategies expressed in (8.13) would work well for the peg edge/hole plane contacts, but when peg edge/ hole chamfer face contacts occur, there arise two situations for which the alignment will be worsened. See Figure 8.12(a) and (b).

These are two accounts on which the strategies (8.13) fail for this combination.

(iii) Chamfered Peg - Chamfered Hole

Here there is no need to delve deeper than to note the distinct possibilities of :

(i) Peg edge/line contacts resulting in peg face/line contact; and

(ii) Peg edge/hole chamfer face contacts. Both of these are referred to above, and are stumbling blocks for strategy (8.13).

In addition, the new situation of a peg chamfer face/hole edge contact will arise. This also adds to the untenability of the proposed strategy. This is illustrated by Figure 8.13(a) and (b).

(iv) Chamfered Peg - Unchamfered Hole

The occurrence of the contact forms discussed above again dismiss the possiblity of strategy (8.13) as a blanket alignment solution for this combination.

This review of the peg-hole combinations with regard to the applicability of the simple general strategy of (8.13) has met with little success. It seems that because three types of contacts are involved with each combination, and that these contacts hold quite different characteristics, a workable general strategy is difficult to find.

Tactually there were three properties that could be sensed by the described arrangement - direct force, shear force and a tipping moment. In strategy (8.13) the presence of these were sensed. It was felt that perhaps if more than the existence of a shear force was sensed, the additional information may provide the increased capability required. This solution would monitor both the magnitudes of the direct and shear forces sensed at A, and from this, derive the direction of R relative to the peg's axis. Thus, the capability is extended such that the direction of the contact reaction R can be known. However, a consideration of the contact forms will show that the only additional value is the ability to achieve peg-hole axes alignment in peg edge/hole chamfer face contact situations. (Provided the hole chamfer angle is known). Consider its application to the assembly of an unchamfered peg - chamfered hole combination: firstly, the allowable peg/hole angular misalignment must be constrained such that the grouping of ψ values for peg/hole plane contacts are different compared to that for peg/hole chamfer face contacts. This can be done by limiting the allowable angular misalignment ξ to, say, 10° and specifying the hole chamfer angle around 45°, so that the sensed ψ directions fall into one of two distinguishable groups. Then, alignment could be achieved in each group by matching the sensed direction to a reference direction.

However, this method fails as soon as another mode of contact - line/line - is considered. In Figure 8.3 the angle ψ associated with various peg edge/hole edge contacts are given. A complete range of ψ values $(0 \rightarrow \frac{\pi}{2})$ can be generated with one peg-hole angular alignment ξ, simply by varying the point of hole edge contact. So, for example, a line/line misalignment of $\xi = 30^{\circ}$ reading $\psi = 45^{\circ}$ is possible and there is no way of distinguishing this particular misalignment from a peg edge/hole chamfer face contact for which $\psi = 45^{\circ}$ may indicate $\xi = 0^{\circ}$. Again, this extended solution is discounted for lack of generality.

The trial of these two strategies in which both sensed property (forces and moment) is used, showed that the information arising from a single contact is insufficient for alignment detection in a complete peg-hole situation.

It seems that at best a single tactile contact will enable the peg and hole axes to be aligned (i.e. $\xi = 0$), but this, however, is only one part of the placement operation (Phase I) - there is still the radial misalignment to eliminate before entry (Phase II) can take place. To solve the misalignment problem a fuller picture of the misalignment will be necessary. To do this through tactile contact, numerous contacts would have to be made to feel out the presented geometry - as a blind man would. The blind man, however, besides possessing the most sophisticated tactile sensing apparatus known, has as a processor of this input data, his formidable brain.

So, as a mode of sensing for the mid-range assembly solution that is sought, the tactile method is of limited value. That is, to be of use in the desired context, its application must be to a constrained area. Because of the diverse nature of the different contact forms possible in a single peg-hole situation, sensing a contact reaction alone will <u>not</u> enable the peg-hole alignment to be deduced.

CHAPTER NINE

CHAMFERS

9.1 Introduction

In the study of body contact, Section 7.2, where the direction of the contact force was examined, the importance of the geometrical form at each interaction was accentuated. Certain geometrical forms - chamfers - have proved to be helpful aids to human assemblers. Therefore, the mechanics of chamfers will now be examined.

Another conclusion drawn from Section 7.2 was that if a contact point, for reasons of geometry or friction factor, could not react sufficiently against a forcing effort, such that an unbalanced contact tangential force remained, then if the peg was flexibly held, motion would arise in the direction of the net force. An optimisation of this effect is the 'principle of action of chamfers'. This will be further examined shortly.

Primarily, chamfers are used as devices to increase the assembly target area and help locate the peg into the hole; i.e. to help perform placement Phase I. So, in the terms of Chapter 6, the chamfer can be viewed as a major element in a low explicit consciousness solution system for dealing with small radial misalignments in simple assemblies. For the assembly of a peg into a hole, for instance, the other system element is the lateral flexibility of the held peg which, when interacting with the modified hole (chamfered), tends to reduce the radial alignment error, and thus effect assembly. Of course, angular misalignment is not catered for, and as a result, only a certain latitude to this error is tolerated.

Consider a cylindrical peg-hole assembly with no chamfers and no clearance. Obviously, the latitude for any misalignment in assembling the pair is nil - they must be perfectly aligned. Consequently, assembly is very difficult. This difficulty may be overcome by an intelligent assembler using an efficient search strategy; but for a simple placing device the task would be insurmountable. If, however, the hole is given a chamfer, immediately the tolerance to radial misalignment is increased by the chamfer width. If, in addition, the peg is also chamfered, the alignment constraint is widened further. Reference to Section 4.4 will give a quantitative measure of the increase ease of 'hitting the target' when a considerable clearance is used. In this case the clearance is only 'apparent'.

So it is established that the use of chamfers enhances target acquisition. At this juncture, the question of the geometric nature of the chamfer comes to mind - how is the enlarged target area and the real component area connected? Traditionally the chamfer has appeared in the form of :

(i) a part of a cone (frustum); or

(ii) a flat plane,

but are these the optimal shapes assembly-wise? Therefore, theoretical models will be set up for the various peg-hole chamfer combinations, and the forces involved will be examined and the relevant parameters related to give the optimum entry conditions.

It is said that the chamfer is an aid for executing, if not the whole, then the final stage of placement Phase I. After the chamfer interaction, the peg-hole alignment, at least in one mode, should be such that Phase II can be directly carried out. As already seen in Part I, Phases I and II are related through the matching of alignment conditions at their interface. Therefore, at the end of the chamfer contact, the peg alignment must lie within the specific envelope as dictated by the peg-hole geometry, etc. through Phase II. The chamfer interaction would have been responsible for at least one mode of alignment. In this manner the definition of the exit alignment condition affects the chamfer design.

Regarding the method of peg manipulation, it will be seen in the next section that one necessary condition is peg flexibility so that peg motion can be guided by the chamfer geometry. In this chapter the effects of chamfers on a held peg is investigated; the following chapter will deal with the behaviour under loose confinement. Generally speaking, an assembly system using a tightly gripped mode of peg control would embody a high level of machine consciousness, so that the contact forces are monitored, for control purposes and for prevention of component damage through over-forcing.

Thus it is hoped that an objective approach to the chamfer concept, by way of a generalised analysis format, may yield new configurations best suited to the various applications and, if not, it will at least attest the tried geometries, giving them greater rigour than intuition.

9.2 The Principle of Action of Chamfers

In Section 7.2 the behaviour of solid bodies in contact was analysed. The stability of the contacting situation was found to be dependent on many factors. If a contact point, for reasons of geometry or friction factor, could not react sufficiently against a forcing effort, such that an unbalanced contact tangential force remained, then if the peg was flexibily held, motion would ensue in the direction of this net force. This is essentially the principle of action of chamfers. This mechanism will be further investigated, and the effect optimised for various contact situations.

Consider a peg axial force P pushing a peg onto a surface resulting in a contact normal force, P_y, and a contact tangential force, P_x, where vectorially :

$$P = P_y + P_x \tag{9.1}$$

P_y is resisted by the contact normal reaction force N, such that :

$$N = -P_y \tag{9.2}$$

and P_x is resisted up to a limit by the contact reaction tangential, or contact frictional force, T. However, T is upperbound such that

$$-T \leq P_x \text{ and } T_{max} = \mu N \tag{9.3}$$

where μ is the coefficient of contact friction.

The contact geometry governs the magnitudes of P_y and P_x within Equation (9.1), that is :

$$P_y = P\cos\psi$$

$$\text{and } P_x = P\sin\psi \tag{9.4}$$

Therefore, the contact form could be arranged such that $|P_x| > |T_{max}|$ always holds. This is done by increasing ψ, which increases P_x and decreases P_y. In this way contact motion is dependent on contact geometry.

Now, if the peg was flexibly held (or slaved off the felt forces) the unbalance contact tangential force, ΔT, would move the system in its direction

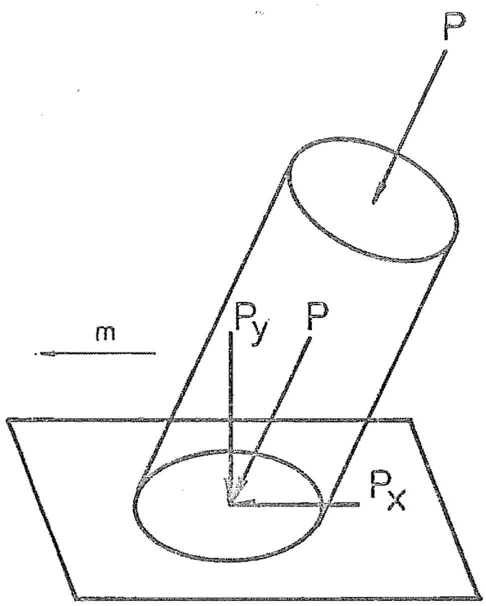
$$\Delta T = P_x - T \tag{9.5}$$

Of course, this direction is designed so the peg moves into the hole.

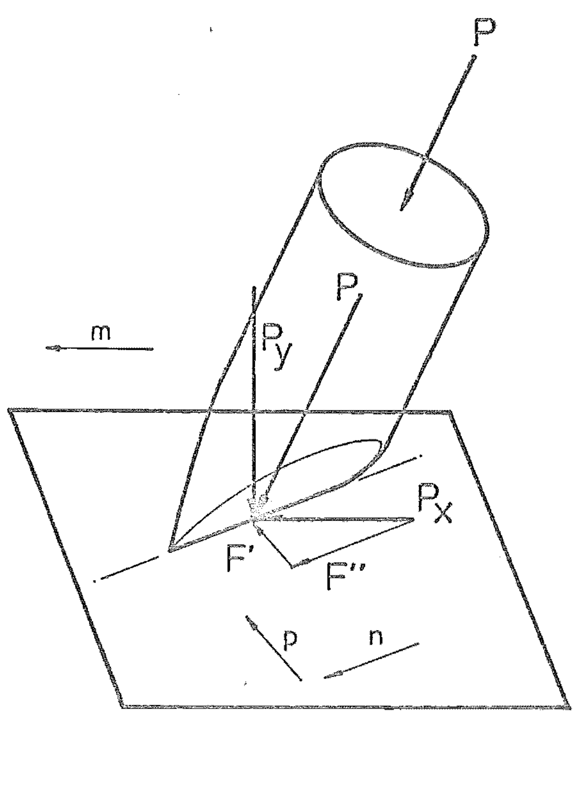
To respond to the unbalanced force as determined by the chamfer design, the peg must be flexibly held (or appear to have flexibility), but only in a defined manner. To follow the contact tangential force ΔT, and to ride the geometry, motion must be allowed in the peg axial and lateral directions. However, the peg's angular attitude must be

FIG. 9.1 FORCES AT THE CONTACT FACE

(a)



(b)



held constant unless consciously changed.

Now the mechanics will be examined more closely. Figure 9.1(a) illustrates a case; $N = -P_y$ and if $|\mu N| < |P_x|$, the peg system moves in the $\vec{m}$ direction. Representative of this model are contact forms in which the coefficient of friction is non-directional, e.g. plane/plane contacts. In Figure 9.1(b) the peg is in contact with the plane through a knife edge which is at an angle to the trace of the plane containing P_y and P. P_y is balanced by N.

Now P_x is resolvable into two in-plane components; F" in the $\vec{n}$ direction, and F' normal to it in the $\vec{p}$ direction. The frictional effects opposing F" and F' are $\mu_n N$ and $\mu_p N$ respectively. μ_n and μ_p are the respective frictional coefficients in the $\vec{n}$ and $\vec{p}$ directions; they are usually numerically different. Depending on the relative sizes of the contact tangential components and their respective frictional reaction forces, the direction of motion is determined. For example, if $|F'| < |\mu_p N|$ and $|F"| > \mu_n N$, then motion will take place in the $\vec{n}$ direction. This type of behaviour is found in line/line and line/plane contacts.

Now the chamfer motion will be studied for the various contact forms,and for chamfers its angle will be optimised for motion.

9.3 Line/Line Contact

The behaviour of a flexibly held peg in line/line contact will now be examined.

For peg edge/hole edge contacts the direction of the contact normal in relation to the peg axis is given by Equation (7.8):

$$\tan\psi = \frac{m_h}{n_h} = \frac{\cos\beta_h}{\cos\gamma_h} \tag{9.6}$$

and illustrated in Figure 7.5(a) and (b). The contact normal, $\vec{ON}$, lies in the radial plane of the peg that also contains the contact point 0. So according to Equation (9.4):

$$P_y = P\cos\psi = -N$$

$$\text{and } P_x = P\sin\psi.$$

See Figure 9.2. For a situation of peg axial effort P, P_y, P_x and P, lie on the peg's contact radial plane, and in addition, P_x lies in the contact tangential plane that contains the two contacting line segments, $\vec{OH}$ and $\vec{OC}$.

Therefore, the contact tangential P_x is trying, against the contact frictional force $T = \mu N$, to cause relative motion of the line contact at 0. The magnitude of this effort, according to Equation (9.5) is

$$\Delta T = P_x - T$$

Considering a peg edge/hole edge contact; any motion would change the contact point so that the instantaneous direction of ΔT relative to the hole changes with the variation in relative $\vec{OC}$ and $\vec{OH}$ directions, and not on any alterable geometry. Usually the contact point moves around the hole edge until two simultaneous line/line contacts result.

9.4 Line/Plane Contact

Into this domain fall the types of edge/chamfer plane contacts which form the main topics of interest in this chapter - chamfers. For generality, the other line/plane contacts will also be examined.

Section 7.5 discussed the direction of the contact normal for this category of contacts. The angle ψ between the contact normal and the peg axis directions is given by Equation (7.9):

FORCES ON A FLEXIBLY HELD PEG IN CONTACT, FIGS.9.2-9.6

FIG.9.2 LINE/LINE

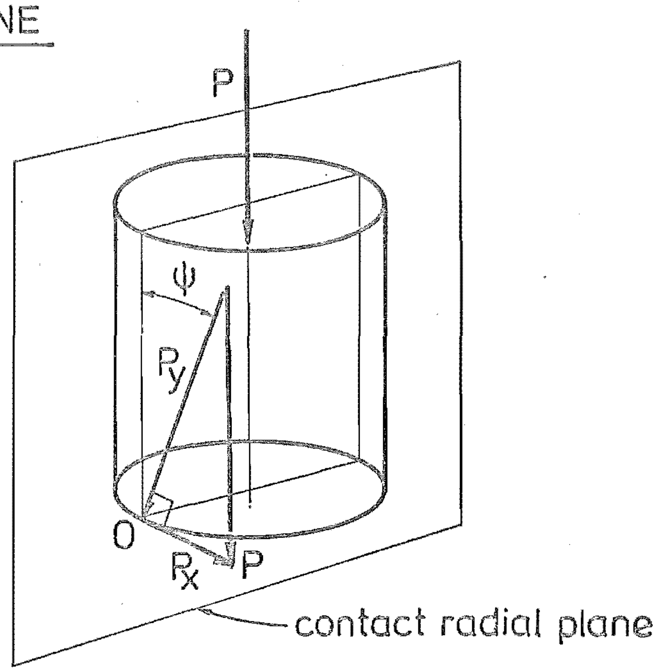
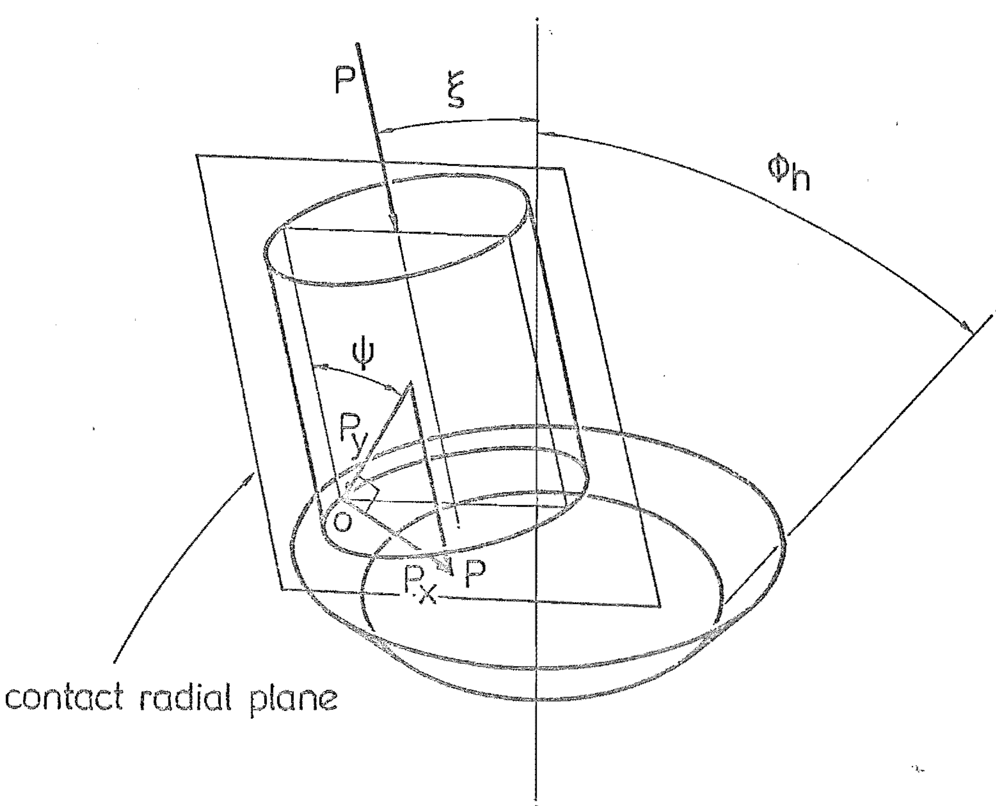


FIG.9.3 PEG EDGE/HOLE CHAMFER FACE



$$\cos\psi = \ell_p . \ell_s + m_p . m_s + n_p . n_s \tag{9.7}$$

where (ℓ_p, m_p, n_p) and (ℓ_s, m_s, n_s) are the directional cosines of the peg axis and the normal to the contacted plane respectively.

(1) Peg Edge/Hole Plane Contact

The peg edge/hole plane contact is illustrated in Figure 9.1(a). There is motion only if $\Delta T \neq 0$, i.e. if

$$|P_x| > |T_{max} = \mu N|$$

This, of course, depends on the magnitude of ψ.

(2) Peg Edge/Hole Chamfer Face Contact

This contact form, associated with the unchamfered peg - chamfered hole, is illustrated in Figure 9.3.

At the contact point 0, the forcing effort P manifests itself as a contact normal and a contact tangential component, P_y and P_x respectively. They lie in the contact radial plane of the peg which is not necessarily the plane containing the maximum angular misalignment ξ. P_y is balanced by N; P_x is partially resisted by T (= μN), such that ΔT remains to cause peg motion in the P_x direction.

The magnitude of ΔT, according to Equations (9.4 - 9.5) is :-

$$\Delta T = P(\sin\psi - \mu\cos\psi) \tag{9.8}$$

and ψ is given by Equation (7.10) :

$$\cos\psi = \cos\left(\frac{\pi}{2} - \xi\right).\cos\alpha_s + \cos\xi.\cos\beta_s \tag{9.9}$$

β_s is constant for a symmetrical chamfer, and is related to the hole chamfer angle ϕ_h by

$$\phi_h = \frac{\pi}{2} - \beta_s \; ; \; \beta_s = \frac{\pi}{2} - \phi_h \tag{9.10}$$

Accordingly (section 7.5) , α_s varies as :

$$\phi_h \leqslant \alpha_s \leqslant \pi - \phi_h \tag{9.11}$$

Thus, by applying the limits of expression (9.11) to Equation (9.9) the range of possible ψ values is determined, and this subsequently is used to ensure $\Delta T > 0$ through Equation (9.8).

The rearrangement of Equation (9.8) shows :

$\Delta T = 0$ when $\sin\psi = \mu\cos\psi$

$$\text{i.e. } \mu = \tan\psi \; ; \; \psi = \tan^{-1}\mu = \alpha_f \qquad (9.12)$$

So for $\Delta T > 0$, ψ must always be greater than α_f.

The direction of P_x and thus ΔT, must necessarily lie on a plane segment of the hole chamfer, and for

$$\xi < \frac{\pi}{2} - \phi_h \qquad (9.13)$$

ΔT always has a component into the hole. For chamfers of large ϕ_h, and conditions of large ξ, post chamfer peg edge/ hole edge contact may occur. This behaviour here has already been examined in Section 9.3.

The peg lateral force, ΔT_L, due to ΔT, is important for slaving the peg into alignment. This is related to ΔT by :

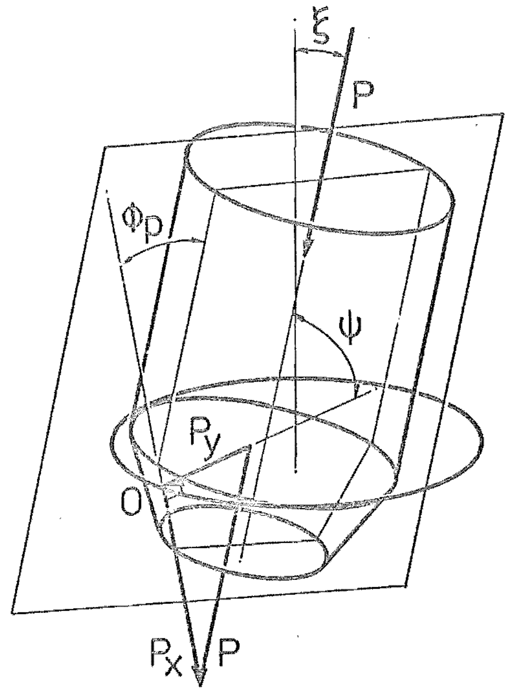
$$\Delta T_L = \Delta T \cos\psi$$

Like ΔT, it does not necessarily point in the direction of maximum misalignment.

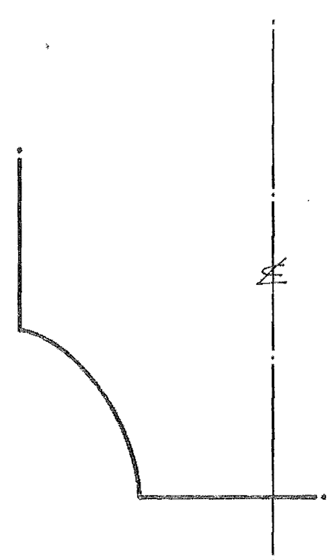
On the topic of chamfer shape for this peg/hole combination, it is conceivable that a system where ΔT tends to zero as the misalignment is reduced can be operated. This could be achieved through the variation of ψ in Equation (9.8); ψ is defined by Equation (9.9) relating it to ξ and α_s. But since α_s and ξ cannot be fixed, but occur within bandwidths, ψ and thus ΔT, also become unpredicatable. For this reason, it is difficult to realise this idea. A conical chamfer is equally satisfactory.

FIG. 9.4 PEG CHAMFER FACE / HOLE EDGE

(a)



(b)



(3) Peg Chamfer Face/Hole Edge Contact

Section 8.3, subsection 2, discusses the direction of the contact normal in this type of contact. The contact normal direction, lying in the contact radial plane of the peg, makes an angle ψ with the peg axis direction and is independent of the peg-hole alignment. ψ is therefore a constant

$$\psi = \frac{\pi}{2} - \phi_p \tag{9.14}$$

where ϕ_p is the peg chamfer angle. See Figure 9.4.

So, irrespective of alignment, as long as there is peg chamfer face/hole edge contact, the following holds

$$P_y = P\cos\psi = P\sin\phi_p \tag{9.15}$$

and $P_x = P\sin\psi = P\cos\phi_p$

The reaction forces will be

$$N = -P\sin\phi_p$$

$$T_{max} = \mu N = -\mu P\sin\phi_p.$$

Therefore:

$$\Delta T = P(\cos\phi_p - \mu\sin\phi_p) \tag{9.16}$$

$$\Delta T = 0 \text{ when } \cos\phi_p = \mu\sin\phi_p$$

$$\text{i.e. } \mu = \cot\phi_p; \quad \phi_p = \cot^{-1}(\mu) \tag{9.17}$$

Therefore:

$$\Delta T > 0 \text{ so long as } \phi_p > \cot^{-1}(\mu).$$

It must be remembered that the plane of contact is not necessarily the plane containing the maximum misalignment ξ; however, if it is not, motion down the chamfer face will change the contact point so altering the direction of ΔT, directing the peg into the hole. This is due to the closed perimeter nature of the hole edge, and the existence of the lead-in on the peg.

The peg lateral component of ΔT, required for the slaving of the peg motion, for this arrangement, is :

$$\Delta T_L = \Delta T \sin \phi_p \tag{9.18}$$

The direct relationship between ΔT_L and ϕ_p expressed through Equations (9.16 and 9.18) combine to give :

$$\Delta T_L = P(\cos \phi_p - \mu \sin \phi_p) \sin\phi_p \tag{9.19}$$

This enables a variable correction force idea to be used. The magnitude of ΔT_L could be varied directly as ϕ_p is changed, such that $\Delta T_L \to 0$ as entry is approached. A chamfer shape likened to that shown in Figure 9.4(b) will result.

(4) Peg Edge/Hole Wall Contact

This contact form is shown in Figure 9.5. The angle ψ is given by Equation 8.7 -

$$\cos\psi = \ell_p.\ell_s + n_p.n_s \tag{9.20}$$

where $(\ell_s 0, n_s)$ is the directional cosine of the normal to the contacted hole wall elemental plane, and (ℓ_p, m_p, n_p) is the directional cosine of the peg axis.

Since the peg misalignment is small (for this contact form to be possible), ψ will invariably be large, thus a large P_x component guiding entry will result.

9.5 Plane/Plane Contact

In the theme of this chapter the plane/plane contact that is of interest is the contact of two chamfer planes. The peg face/hole plane form does not give rise to a motive contact force; the peg wall/hole wall form is a trivial case.

Figure 9.6 illustrates this contact form. The forces P_y, P_x and P lie in the contact peg radial plane, and ψ is constant,

FIG. 9.5 PEG EDGE / HOLE WALL

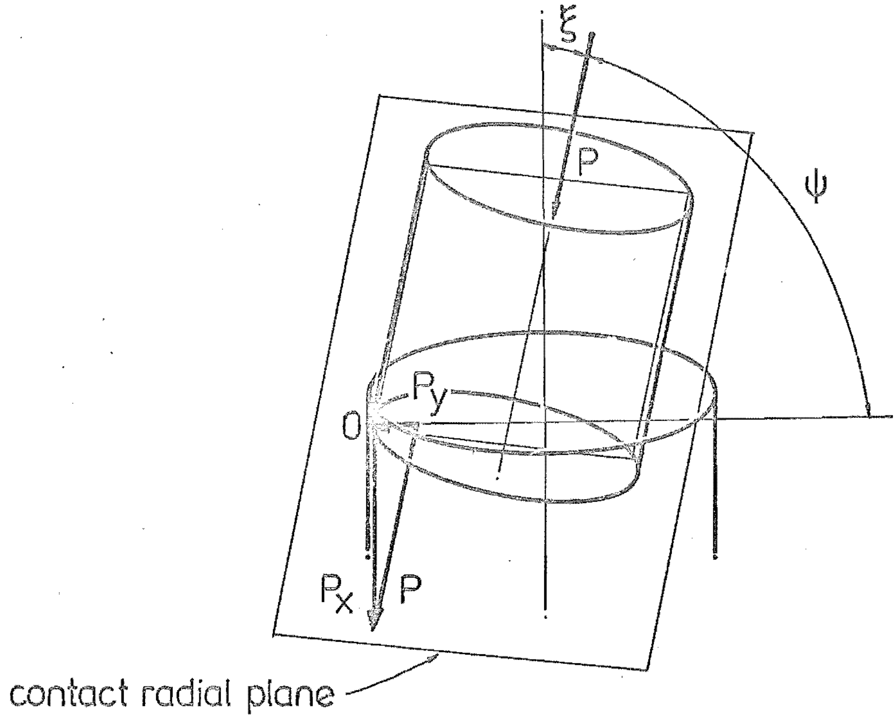
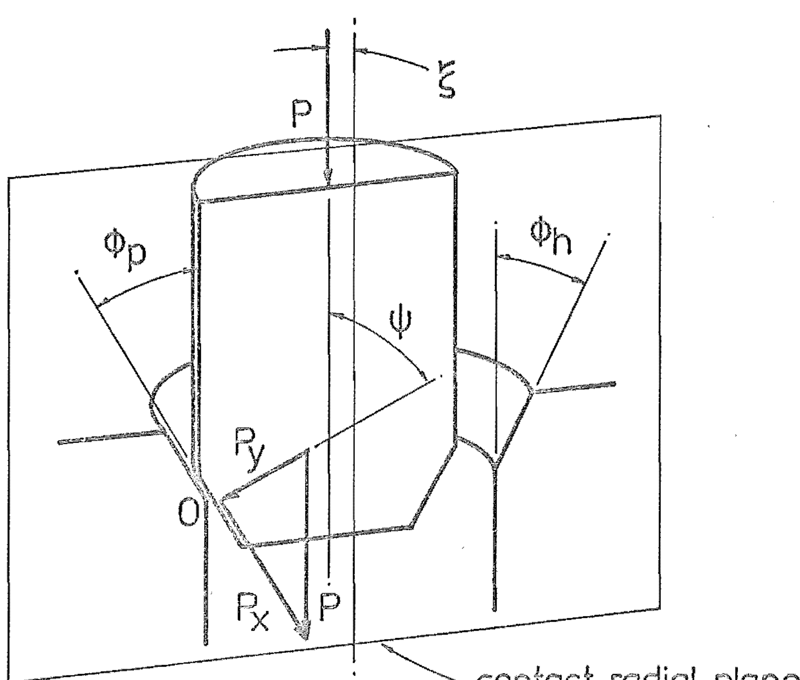


FIG. 9.6 PEG CHAMFER FACE / HOLE CHAMFER FACE



given by $\psi = \frac{\pi}{2} - \phi_p$. For this contact form to occur, the contact and the misalignment planes are coplanar; ξ is related -

$$\xi = \phi_h - \phi_p \tag{9.21}$$

If $\phi_h = \phi_p$ by design, then an achievement of this plane/plane contact implies $\xi = 0$. If $\xi \neq 0$, and $\phi_h = \phi_p$, then the contact form will be either peg edge/hole chamfer face (9.4:2) or peg chamfer face/hole edge (9.4;3).

For this form ΔT is similarly calculated.

9.6 A Chamfer Solution

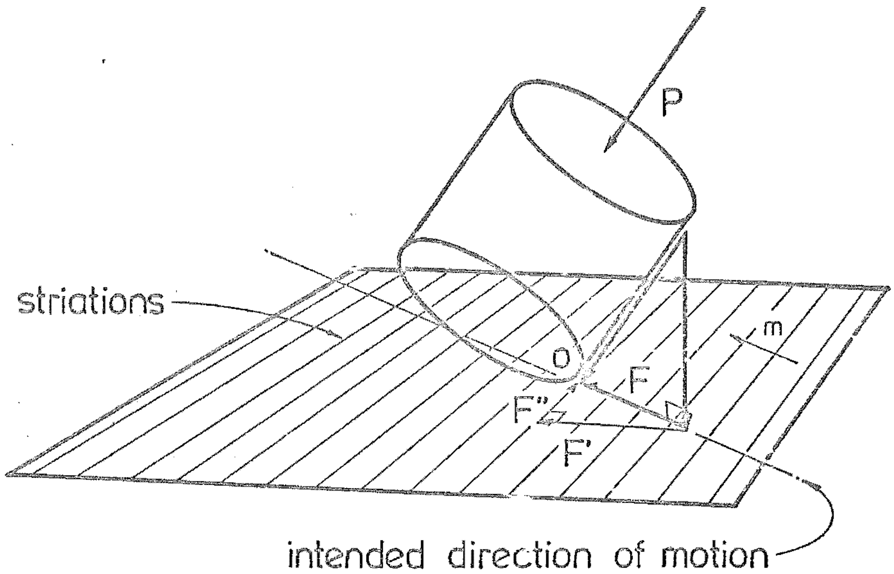
It is interesting to note that for small general misalignments, with the aid of a generous hole chamfer, a simple tactile feedback/ chamfer guided solution can be attained.

If peg edge/chamfer face contact can be guaranteed without the advent of line/line contacts, then the following strategy may show promise. When peg edge/chamfer plane contact is first made, the manipulator adopts the stationary contact mode for tactile sensing (discussed in Chapter 8). The direction of the contact resultant R is measured, and then aligned to a reference alignment direction. (This may be a several steps iterative process if the correction plane is quite different from the misalignment plane in initial directions). On completion of this step the peg and the hole should be axially aligned.

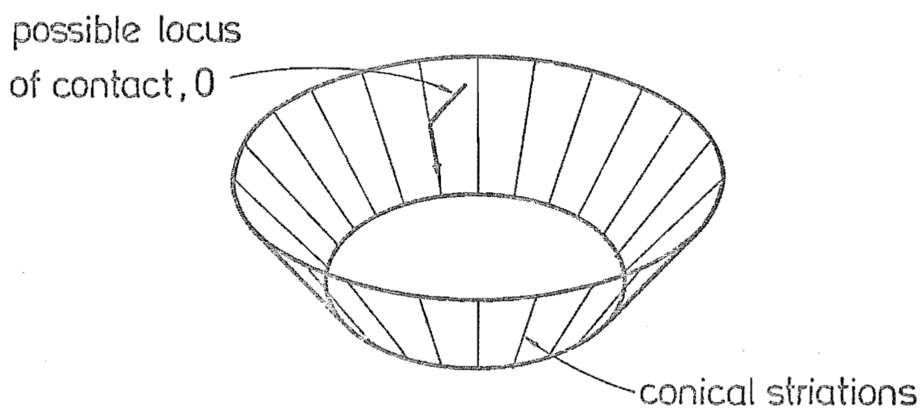
The next step is radial alignment through slaving of the contact force (Section 9.4;2) while maintaining the peg's rotational attitude. Entry should follow.

FIG. 9.7 DIRECTIONAL FRICTION COEFFICIENTS

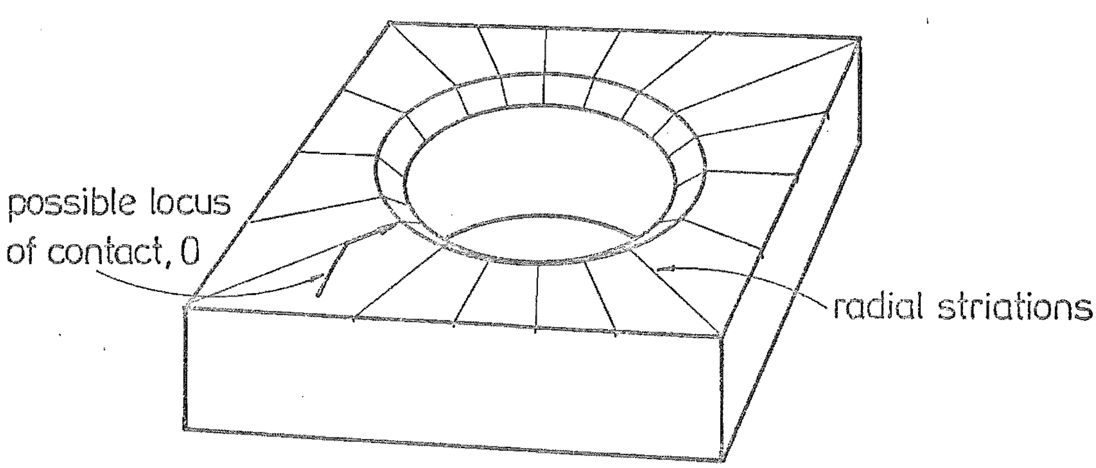
(a)



(b)



(c)



9.7 Directional Friction Coefficients

Discussed in Section 9.2 and illustrated in Figure 9.1(b) is the case of directional friction coefficients. The contact geometry is such that movement is preferentially directed in certain directions - this is manifested in directional friction coefficients.

In Figure 9.1(b) the cause of this was the reluctance of a line/plane contact to move in a direction perpendicular to the contact line, and its preference to move along that line direction. The latter preference is the path of minimum resistance (resistance from the microscopic deformation of surface irregularities)[13].

Consider another example: Figure 9.7(a) A peg in edge/plane contact attempts to track across a striated plate under a force F. When contact is with the smooth and uniform portion of the plane where the coefficient of friction is non-directional, movement is in the $\vec{m}$ direction (assuming the planar component of F is greater than the frictional resistance). However, when a striation is encountered, the force F is resolvable into F" along the striation direction and F' perpendicular to it. Each of these directions exhibits a different coefficient of friction, μ'' and μ' respectively. Typically μ'' is low and μ' is high. If μ' is high enough, the force in the F' direction is opposed, resulting in gross peg motion along the striation (low μ'') direction.

This idea could be used on chamfer surfaces to inhibit the circumferential component of motion on the chamfer face during sliding contacts, so directing all the movement downwards into the hole. See Figure 9.7(b). This could be extended onto the hole plane as an aid for hole searching, Figure 9.7(c). It is envisaged that the quality of the striations is undemanding, for as a friction barrier, almost any score mark will suffice.

9.8 Chamfer Impacts

The equations for the contact impulses are given in Section 7.7 by Equations (7.15 and 7.16).

For chamfer impacts, in general the angle ψ is large, thus giving a small v_n and a large v_t according to Equation (7.12). For this type of glancing impact, v_n is usually small enough not to cause plastic damage (small contact area $\rightarrow$ high contact stress) at the impacted point, such that μ for the tangential impact component remains small, resulting in β approaching unity. (See Section 7.7).

On the other hand, if ψ is small, v_n is large, and therefore from Equation (7.15) :

$$I_n = mv\cos\psi\ (\alpha - 1)$$

is also large. This large impulse at a line/line or line/plane contact wall causes plastic deformation due to the high stress loading. The surface deformation will, in turn, present a large μ to the tangential component of the impact velocity, resulting in a small β value, and thus a large I_t -

$$I_t = mv\sin\psi\ (\beta - 1)$$

This latter impact case is likely for shallow chamfers (i.e. large ϕ_p, ϕ_h) and especially for line/line contacts.

CHAPTER TEN

LOOSE CONFINEMENT MANIPULATION

10.1 Introduction

Loose Confinement Manipulation is a method of planar search and transport where the peg is guided within loose bounds. It is envisaged that if a peg-hole system is designed such that contact forces between the peg and the hole are sympathetic to entry, then a simple method of utilising these forces for assembly is to hold the peg loosely so that these forces are effective. This implies that the assembly is achievable with the presence of a greater misalignment than is normally acceptable to a firmly held peg. The alternative to loose confinement is to hold the peg firmly and sense the contact forces, and react in an appropriate manner to achieve assembly. Here a sophisticated feedback sensor and motor system is required.

Loose Confinement Manipulation will operate with the following prerequisites :

(i) Initially the peg is brought into peg face/hole plane contact, such that the peg and hole axes are parallel;

(ii) a direction of planar motion is derived;

(iii) then the peg is shifted along the plane under loose confinement maintaining the axes parallel.

When hole contact is made , if the peg lies within the placement Phase II entry envelope, gravity will provide the assembly effort. This implies two advantages: one, entry is automatic once the required alignment is attained; and two, for reasonably sized components the magnitude of the assembly effort is limited to the component weight - a natural safeguard against over-forcing.

The limited freedom to manoeuvre provided by the loose confine will allow the contact forces to effect the entry once misalignment is sufficiently reduced. The upper limit for peg movement within the loose confine is defined from the placement Phase II non-jamming entry envelope.

There are alternative methods of carrying out this placement Phase I operation in the loose confinement mode. The above outline lists step 2 as a sensing or searching phase, where the relative direction of the hole to the peg is derived. Step 3, of course, is the physical shifting of the peg along this direction towards the hole.

One method of operation uses an unchamfered peg-hole combination. The relative direction of the peg-hole radial displacement is found, and the peg is shifted in peg face/hole plane contact along this direction for an arbitrary distance. If the peg comes within the unchamfered peg - unchamfered hole entry envelope during this shift, then the gravity force effects assembly. If assembly does not occur then the process is repeated with another search and a new shift direction. With an accurate search method close tolerance fitting should be achievable.

Another method utilises the chamfer effects of chamfered components. The combination here may be :

(a) chamfered peg - unchamfered hole

(b) chamfered peg - chamfered hole

(c) unchamfered peg - chamfered hole.

Of course, with the use of chamfers, the probability of the event of a chamfer contact (or partial entry) is magnified; so the difference in this method is that after the search for the hole direction, the lateral peg shift will result almost invariably in chamfer contact. This

FIG.10.1 PEG/HOLE INTERACTION UNDER LOOSE CONFINEMENT MANIPULATION

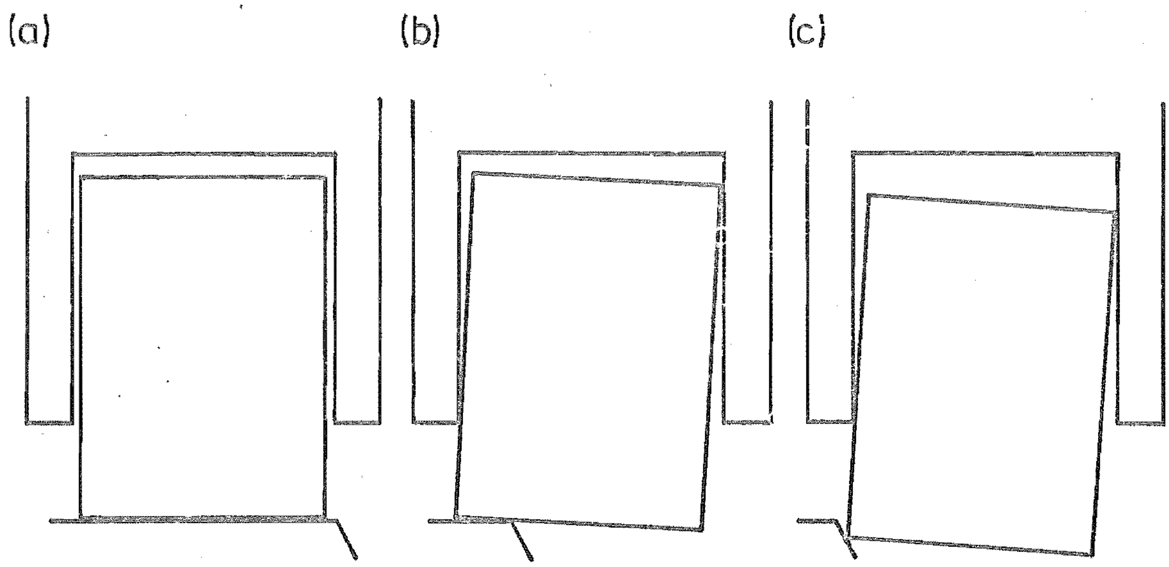
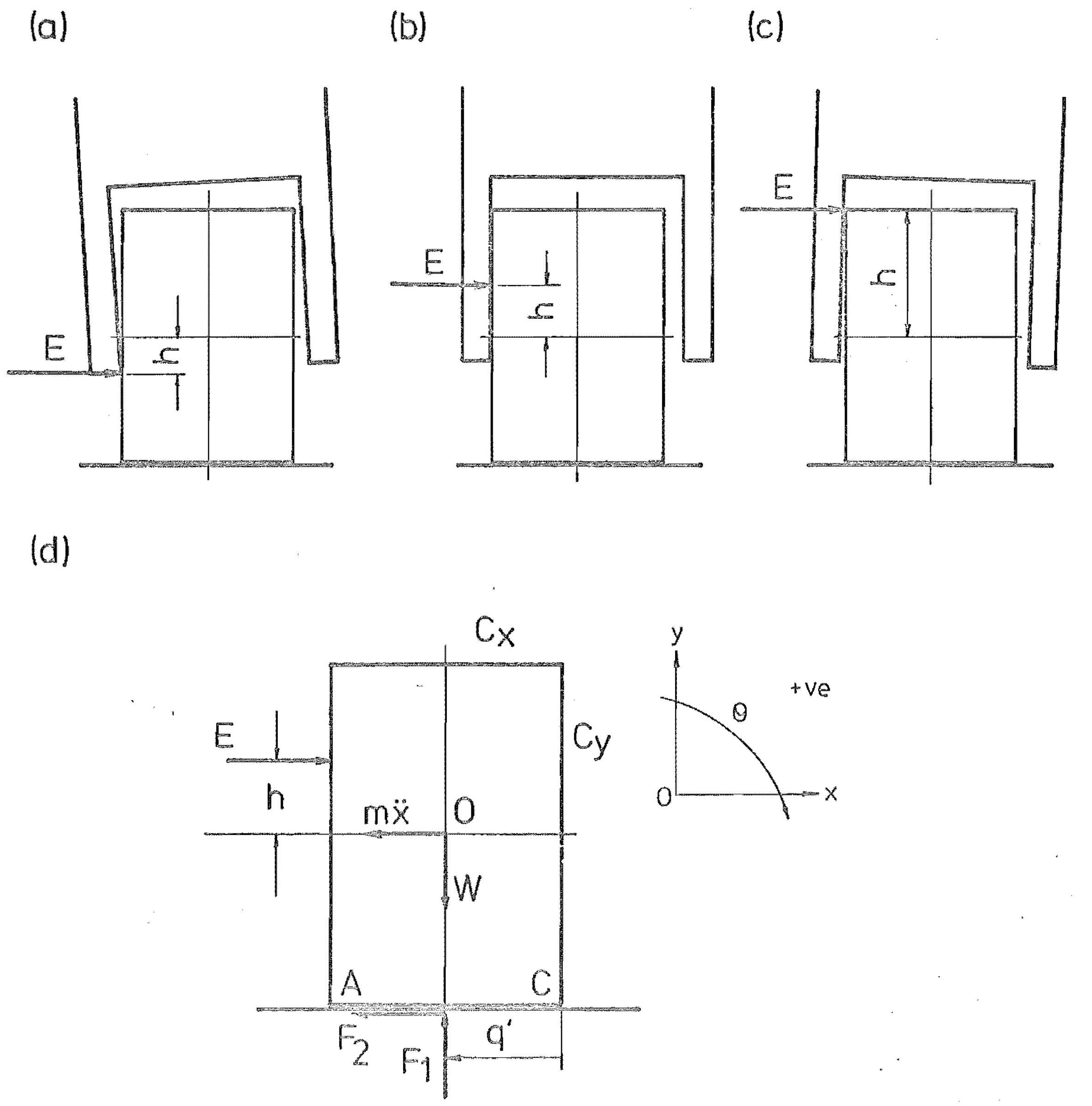


FIG.10.2 PEG/LOOSE CONFINE ALIGNMENT



is manifested in a drop of the peg which, when sensed, terminates the lateral shift. Then the chamfer contact force (originating from a peg axial effort) will slave the now freed peg manipulator such that the peg slides down the chamfer to entry.

This second method of operation of the 'loose confinement mode' does involve more steps and additional equipment. However, if an accurate misalignment direction search procedure cannot be conceived to make the first method efficient, then this second method becomes relevant.

So in this chapter on loose confinement manipulation, the important areas for study are :-

(1) Loosely confined peg moving in peg face/hole plane contact;

(2) " " " " " chamfer contact;

(3) " " " " " the intermediate region between (1) and (2).

(See Figure 10.1)

10.2 Peg Behaviour on the Hole Plane

This is the case of the peg being slid along the hole plane, held within the confine of loose grips; Figure 10.2. Because of allowed hand misalignments the three modes of peg/grip contacts shown in Figures 10.2(a), (b) and (c) will occur, each possessing a different point of effort, E, application. Thus, the set of parameters for when tipping of the peg first occurs, is different for each case. The situation will be analysed to see how the variation in position, h, of effort application affects peg tipping.

Figure 10.2(d) shows a block resting on the hole plane. (A block is used in preference to a cylindrical peg, so that the analysis is expressly two-dimensional - the mechanics of a cylinder within a cylindrical confine will be analogous to this). A force E is applied in the x direction, a distance h above point 0. The hole plane is assumed normal to the direction of gravity - in other words, level. Friction coefficient, μ, between the block surface and the hole plane opposes movement along the plane.

The equations of motion are :

$$\Sigma F_x = E - F_2 - m\ddot{x} = 0 \tag{10.1}$$

$$\Sigma F_y = F_1 - W - m\ddot{y} = 0 \tag{10.2}$$

$$\Sigma M_c = E(h + C_y) - WC_x + F_1 q' - m\ddot{x}C_y - I_c\ddot{\theta} = 0 \tag{10.3}$$

If the block is assumed untipped and just beginning to lift off its surface AC, then :

$$\ddot{y} = 0, \quad \ddot{\theta} = 0, \quad \text{and } q' = 0$$

and also

$$F_2 = \mu F_1, \quad W = mg$$

Substituting these conditions into Equations (10.1 - 10.3) yields :

$$E - \mu F_1 - m\ddot{x} = 0 \tag{10.4}$$

$$F_1 = W \tag{10.5}$$

and $E(h + C_y) - WC_x - m\ddot{x}\, C_y = 0$ (10.6)

Upon rearrangement these equations give :

$$h = \frac{g\, C_x + \ddot{x}\, C_y}{\mu g + \ddot{x}} - C_y \tag{10.7}$$

for $\ddot{\theta} = 0$ motion.

For steady state motion, this reduces to :

$$h = \frac{C_x}{\mu} - C_y$$

It will be helpful to express the values of μ for which rotation will not occur, μ_{nr}, in terms of the other parameters. So that, in a design, if μ is less than μ_{nr}, rotation will not occur; the converse is also true.

FIG.10.3 BLOCK ON PLANE SLIDE

NON-ROTATION FRICTION COEFF. (μ_{nr}) vs ACCELERATION

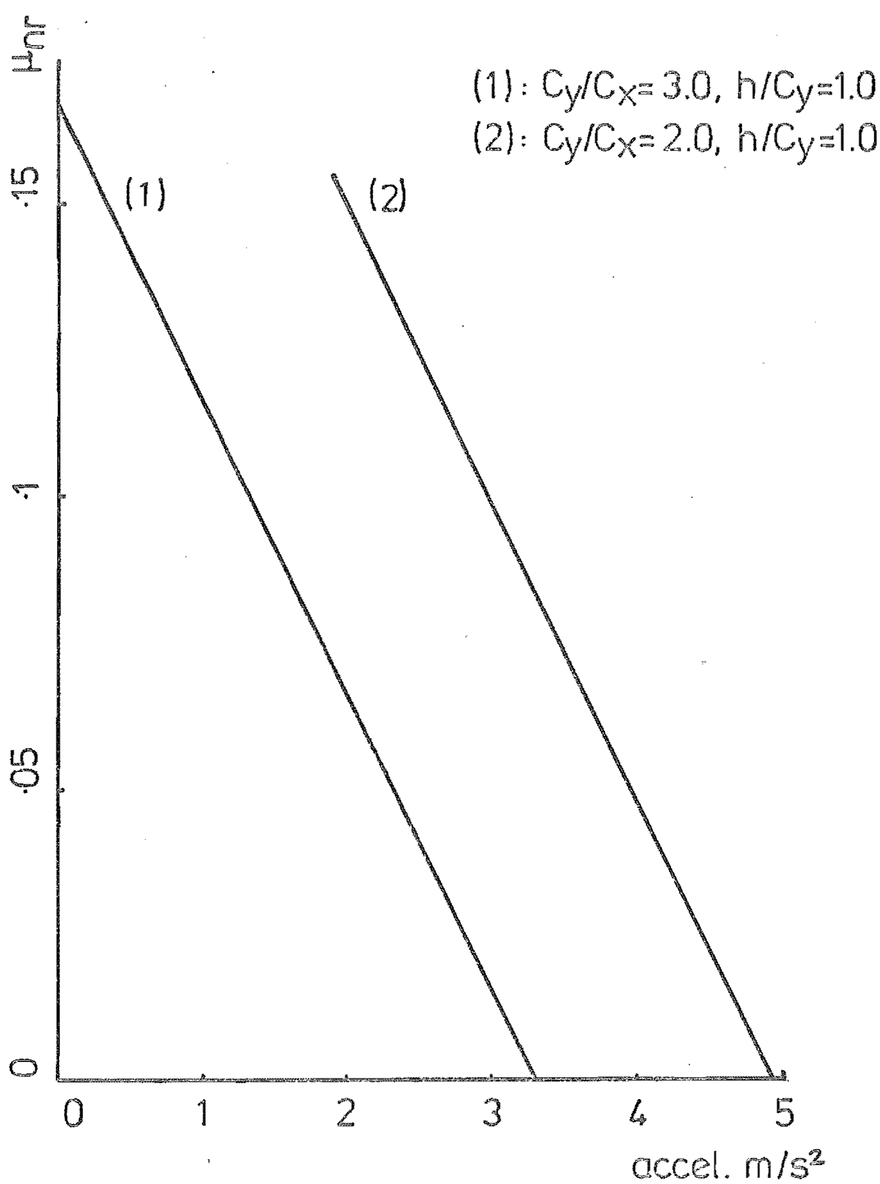
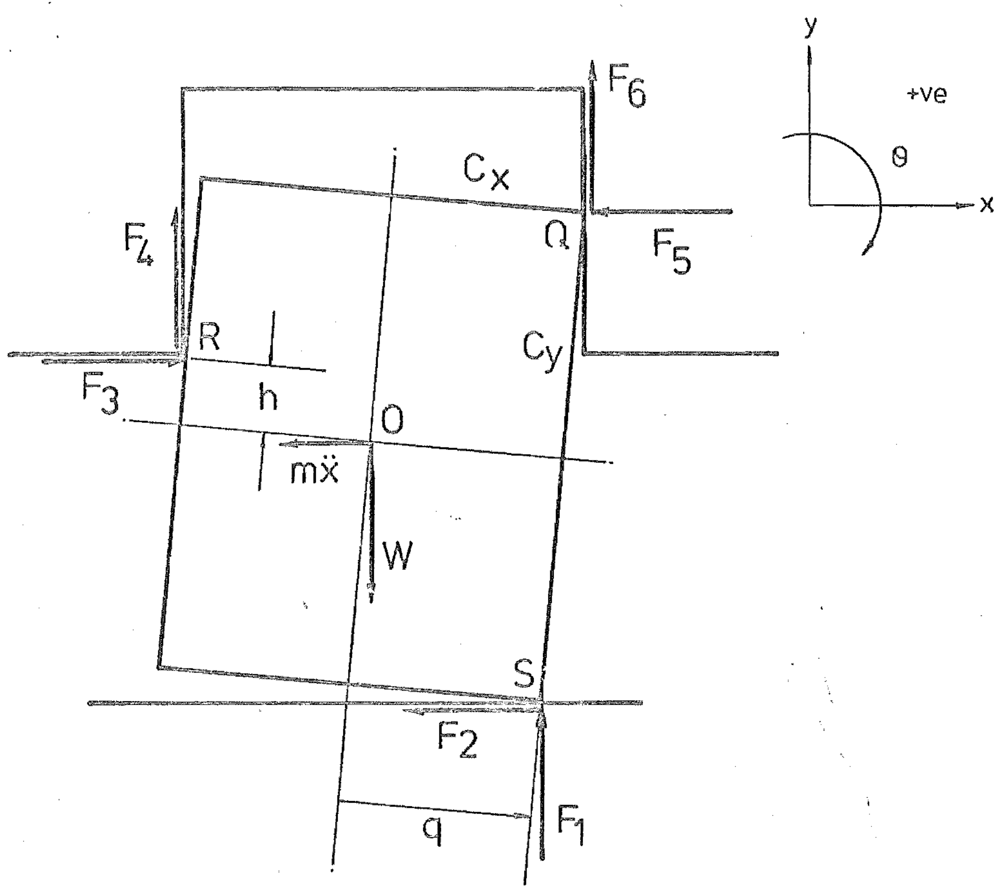


FIG.10.4 CONFINED BLOCK IN TIPPED MODE



A rearrangement of Equation (10.7) will give the no tipping friction coefficient, μ_{nr}, in terms of the remaining parameters, i.e.

$$\mu_{nr} = \frac{gC_x + \ddot{x}C_y}{g(h + C_y)} - \frac{\ddot{x}}{g} \tag{10.8}$$

In Figure 10.3 the variation of μ_{nr} with $\ddot{x}$ is plotted. For steady state motion, and the worst case of effort application (where $h = C_y$), Equation (10.8) becomes

$$\mu_{nr}\Big|_{\substack{\ddot{x}=0 \\ h=C_y}} = \frac{C_x}{2C_y}$$

which for a peg of geometry ratio, say $C_y = 4C_x$, in steady state, μ_{nr} is upper bound by 0.125. From Equation (10.8) the behaviour of the peg is derived.

Now, what happens when either the coefficient of friction, in the case of steady state motion, or the acceleration forces during the onset of motion, causes the block to tip. The block will ride up onto its leading edge and contact the grip confine at two points, as shown in diagram Figure 10.4. This is the model of general tipped motion of the block, between loose confinement grips, on the hole plane. The equations of motion are :

$$\Sigma F_x = -F_2 + F_3 - F_5 - m\ddot{x} = 0 \tag{10.9}$$

$$\Sigma F_y = F_1 + F_4 + F_6 - W - m\ddot{y} = 0 \tag{10.10}$$

and $$\Sigma M_o = -F_1 q + F_2 C_y + F_3 h + F_4 C_x - F_5 C_y - F_6 C_x - I\ddot{\theta} = 0 \tag{10.11}$$

It is assumed in the writing of the above Equations (10.9 - 10.11) that the angle of tip is small enough to be neglected ($\sin\theta \to 0$, $\cos\theta \to 1$ where $\theta \to 0$). Conditions of confinement are

$$\ddot{y} = \ddot{\theta} = 0$$

and in addition:

$$F_2 = \mu_1 F_1, \text{ and}$$
$$W = mg.$$

However, concerning F_4 and F_6, all that can be said about these forces is that they are so bounded , such that :

$$-\mu_3 F_3 \leqslant F_4 \leqslant \mu_3 F_3, \text{ and}$$
$$-\mu_5 F_5 \leqslant F_6 \leqslant \mu_5 F_5.$$

As the situation stands there are three equations and five unknowns. Therefore, the forces F_1,F_3, and F_5, will be derived for the two cases of limiting μ_3 and μ_5 values. One situation occurs when the peg confine moves upwards, producing the situation illustrated in Figure 10.4; the other case occurs when the confine moves downwards producing F_4, and F_6, in the opposite direction. Of course, these upwards and downwards motions are slight and momentary within the general lateral movement of the confine. At these frictional extremes

$$F_4 = \pm\mu_3 F_3 \quad \text{and}$$
$$F_6 = \pm\mu_5 F_5$$

so reducing the number of unknowns to three, namely, F_1, F_3 and F_5.

Therefore, upon substitution of these limiting frictional values, Equations (10.9 - 10.11) become :

$$-\mu_1 F_1 + F_3 - F_5 - m\ddot{x} = 0 \tag{10.12}$$

and $$F_1 + \mu_3 F_3 + \mu_5 F_5 - W = 0 \tag{10.13}$$

and $$-F_1 q + \mu_1 F_1 C_y + F_3 h + \mu_3 F_3 C_x - F_5 C_y - \mu_5 F_5 C_x = 0 \tag{10.14}$$

Rearrangement of Equation (10.13) gives

$$F_1 = W - \mu_3 F_3 - \mu_5 F_5 \tag{10.15}$$

which, upon substitution into Equation (10.12), yields :

$$F_3 = \frac{m\ddot{x} + \mu_1 W - F_5(\mu_1\mu_5 - 1)}{1 + \mu_1\mu_3} \tag{10.16}$$

Substitution of Equations (10.15) and (10.16) into Equation (10.14) and isolating F_5 gives :-

FIG. 10.5 TIPPED BLOCK IN PLANE SLIDE

CONTACT NORMAL FORCES vs FRICTIONAL COEFF.

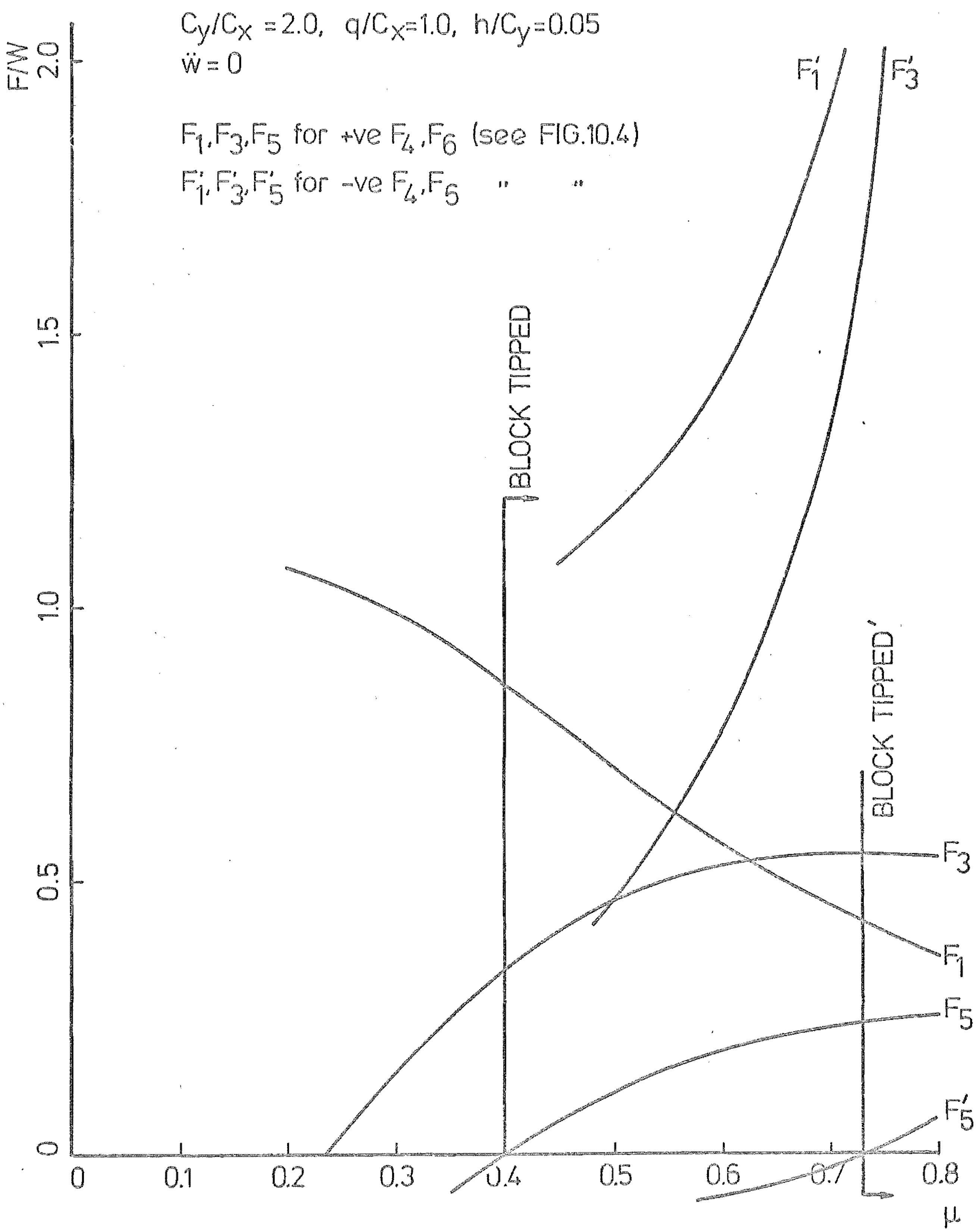
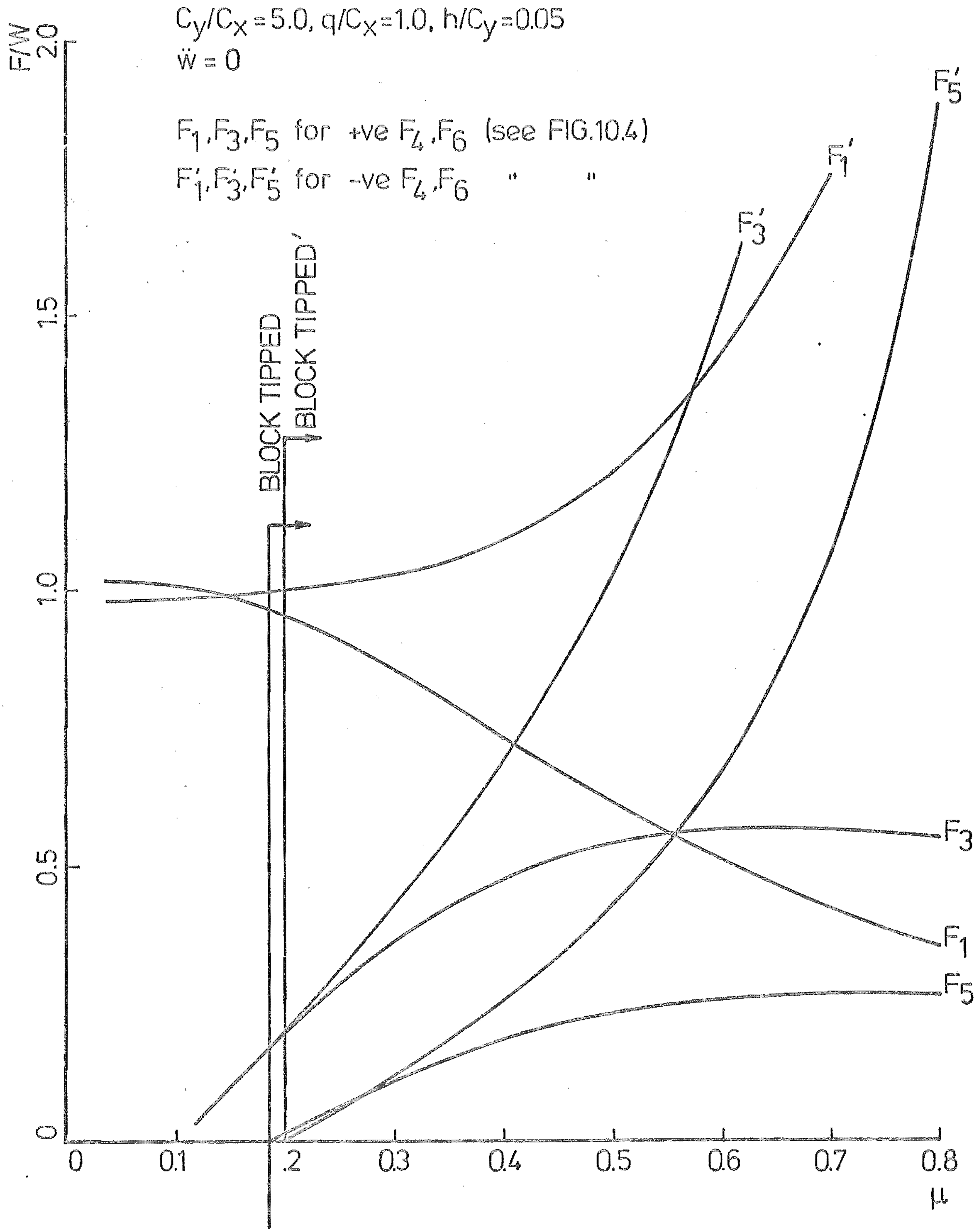


FIG.10.6 TIPPED BLOCK ON PLANE SLIDE

CONTACT NORMAL FORCES vs FRICTIONAL COEFF.



$$F_5 = \frac{C}{A + B} \tag{10.17}$$

where
$$A = \frac{(\mu_1\mu_5 - 1)(h + \mu_3 C_x - \mu_1\mu_3 C_y + \mu_3 q)}{1 + \mu_1\mu_3} \tag{10.18}$$

$$B = C_y + \mu_5 C_x + \mu_1\mu_5 C_y - \mu_5 q \tag{10.19}$$

$$C = (\mu_1 C_y - q)W + \frac{m\ddot{x} + \mu_1 W}{1 + \mu_1\mu_3}(h + \mu_3 C_x - \mu_1\mu_3 C_y + \mu_3 q) \tag{10.20}$$

Upon substitution of F_5 in Equation (10.16), and subsequently, F_3 and F_5 in Equation (10.15), the expressions of F_3 and F_1 are obtained, that is :

$$F_1 = f_1\,(\mu_{1,3,5},\ h,\ C_x,\ C_y,\ q,\ m,\ g,\ x)\ ,$$
$$F_3 = f_2\,(\ "\quad "\quad "\quad "\quad "\quad "\quad "\quad ")$$
and
$$F_5 = f_3\,(\ "\quad "\quad "\quad "\quad "\quad "\quad "\quad ")$$

These expressions are now plotted to show the effect of the various variables.

Figures (10.5) and (10.6) show the effect of variation in the coefficient of friction $\mu(\mu = \mu_1 = \mu_3 = \mu_5)$ on the contact normal forces F_1, F_3 and F_5. F_1, F_3 and F_5 are the values for an upwards frictional force, i.e. μ_3, μ_5 positive; F_1', F_3' and F_5' are the corresponding values for a downwards frictional force, i.e. μ_3, μ_5 negative. Only the sets of forces with F_5, F_5' positive are relevant. It can be seen that in Figure 10.6 in which a block geometry of C_y/C_x = 5.0 is used, the block tips at a lower frictional value than in Figure 10.5, in which the block geometry used is C_y/C_x = 2.0. Also apparent is the force difference brought about by the change in the direction of the confine contact friction forces. The tipped state is obviously more stable under a downwards frictional effect, and the contact normal forces can be higher than the block weight under high friction conditions.

FIG.10.7 TIPPED BLOCK IN PLANE SLIDE

CONTACT NORMAL FORCES vs BLOCK GEOMETRY RATIO

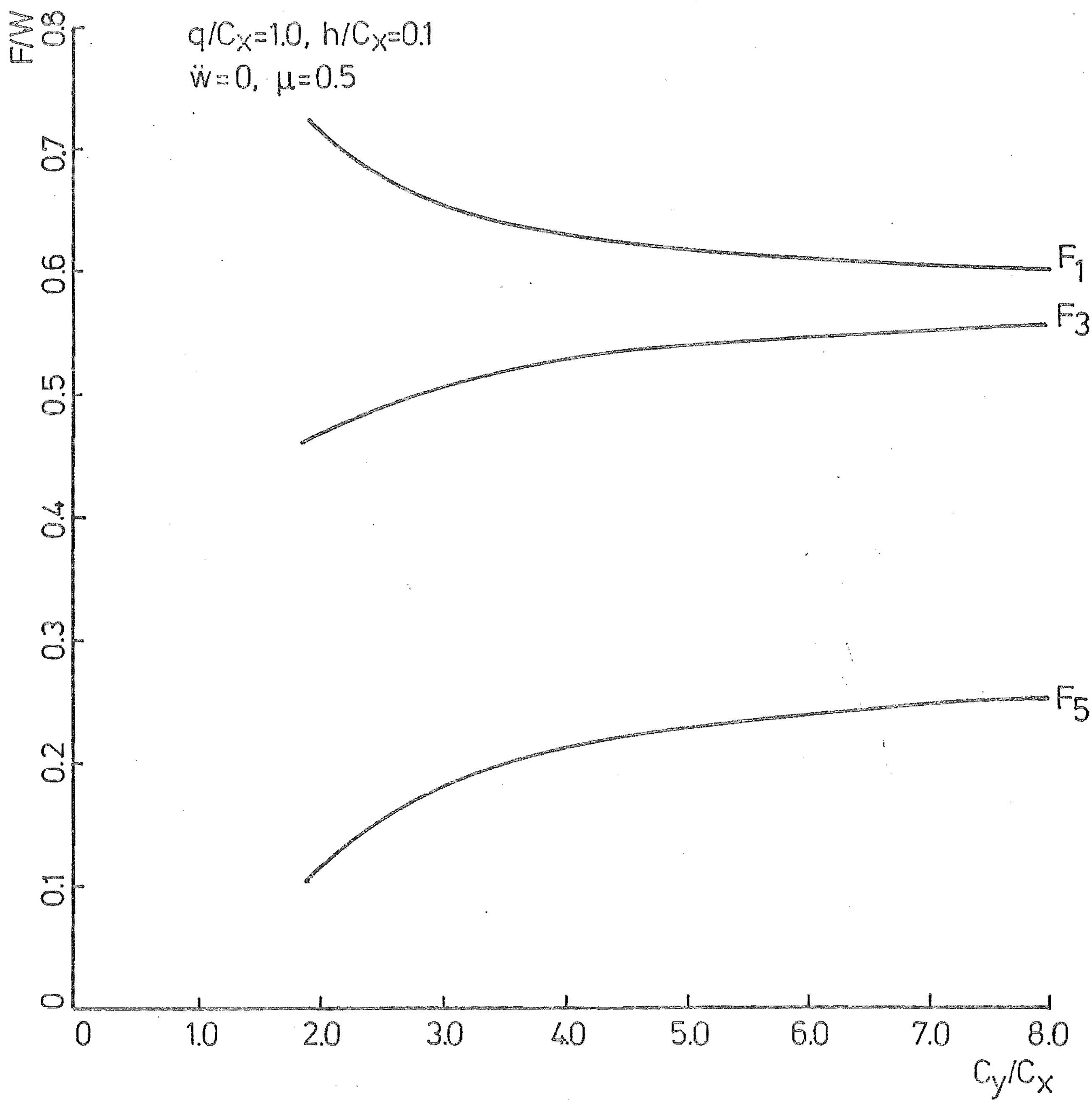


FIG. 10.8 TIPPED BLOCK IN PLANE SLIDE

CONTACT NORMAL FORCES vs BLOCK WEIGHT

$C_y/C_x = 2.0$, $h/C_y = 0.05$, $q/C_x = 1.0$

$\ddot{w} = 0$, $\mu = 0.5$

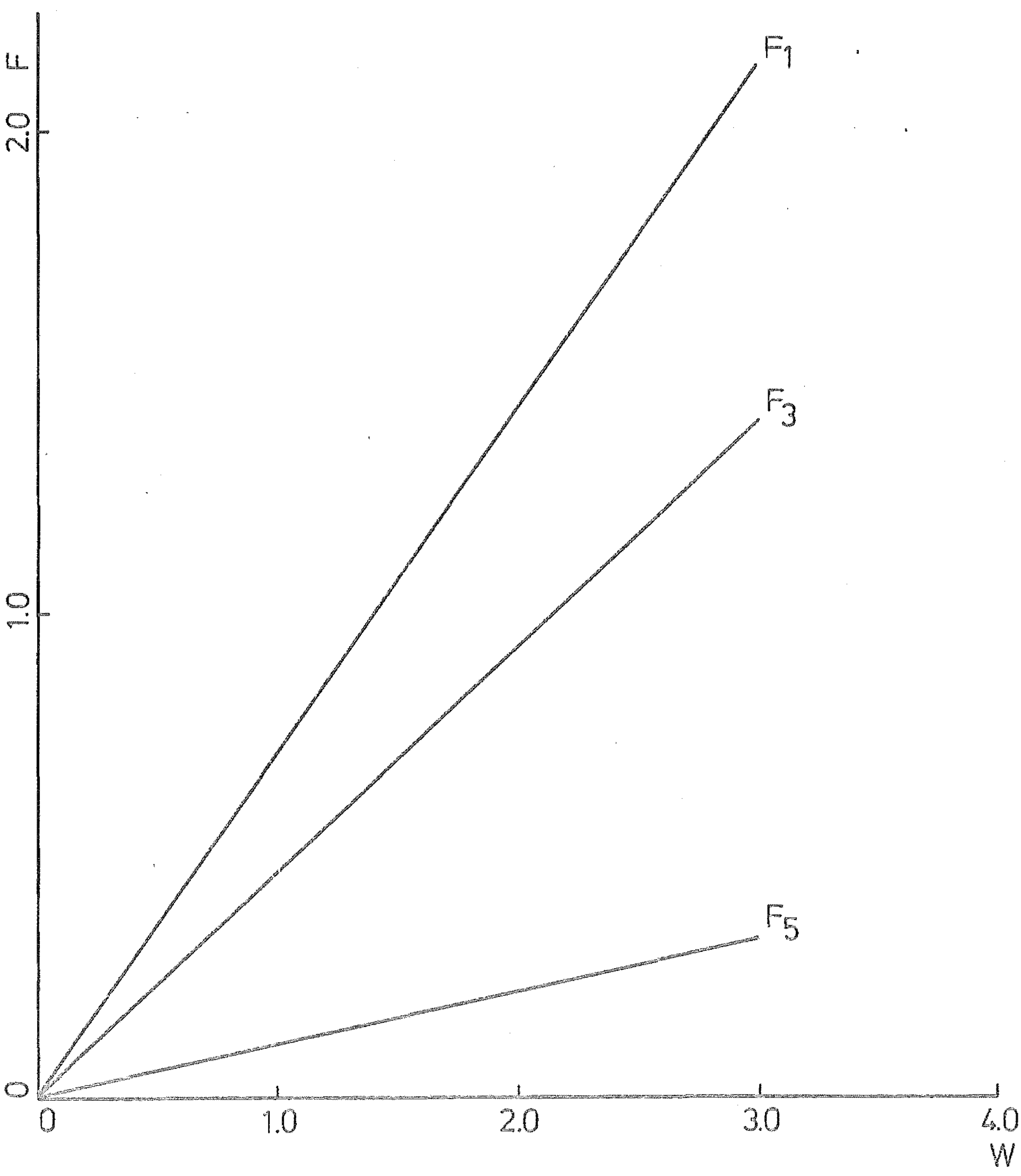


FIG.10.9 TIPPED BLOCK IN PLANE SLIDE

CONTACT NORMAL FORCES vs POSITION OF THE CONFINE (h)

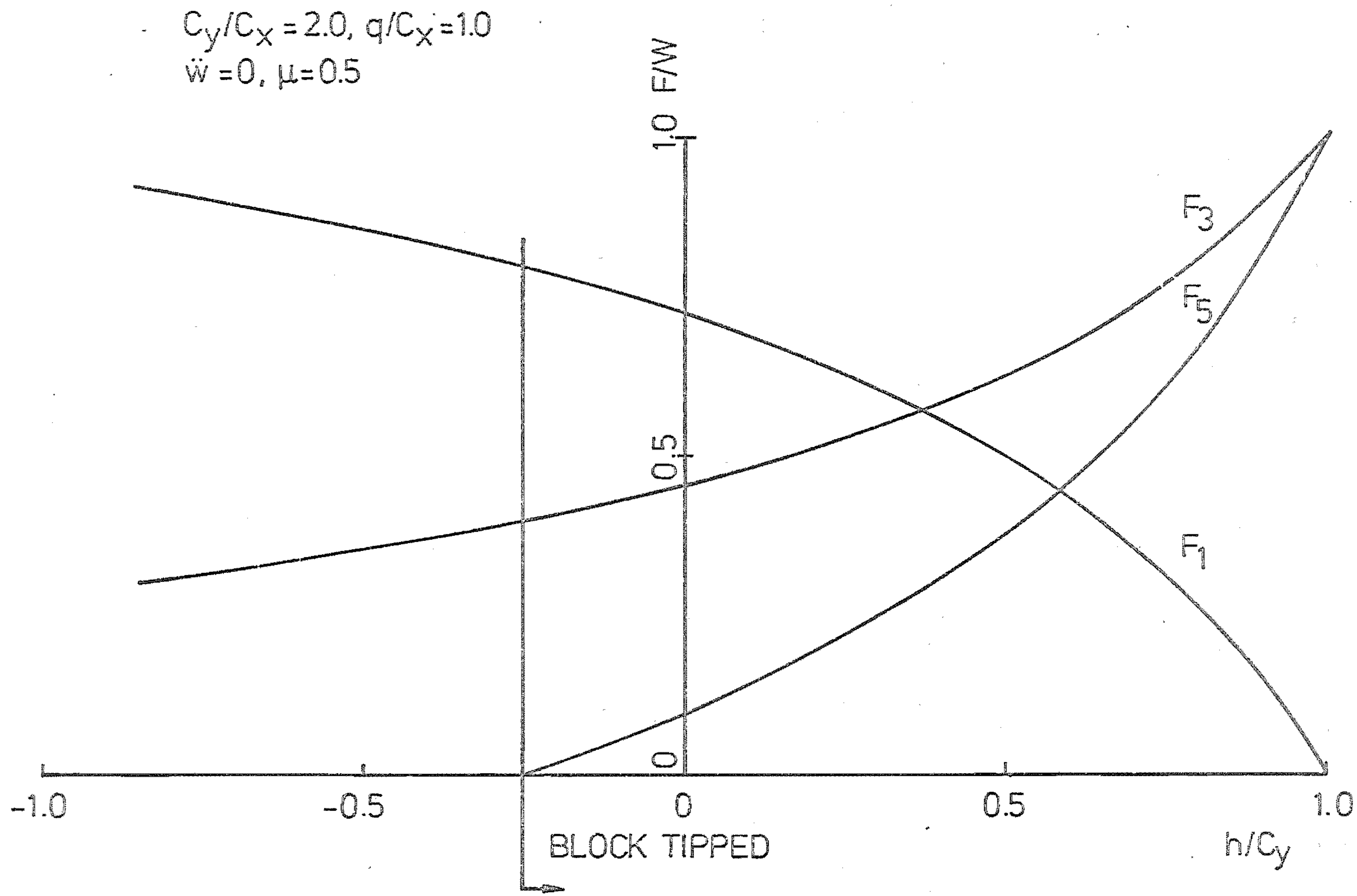


FIG.10.10 TIPPED BLOCK IN PLANE SLIDE

CONTACT NORMAL FORCES vs LATERAL ACCELERATION

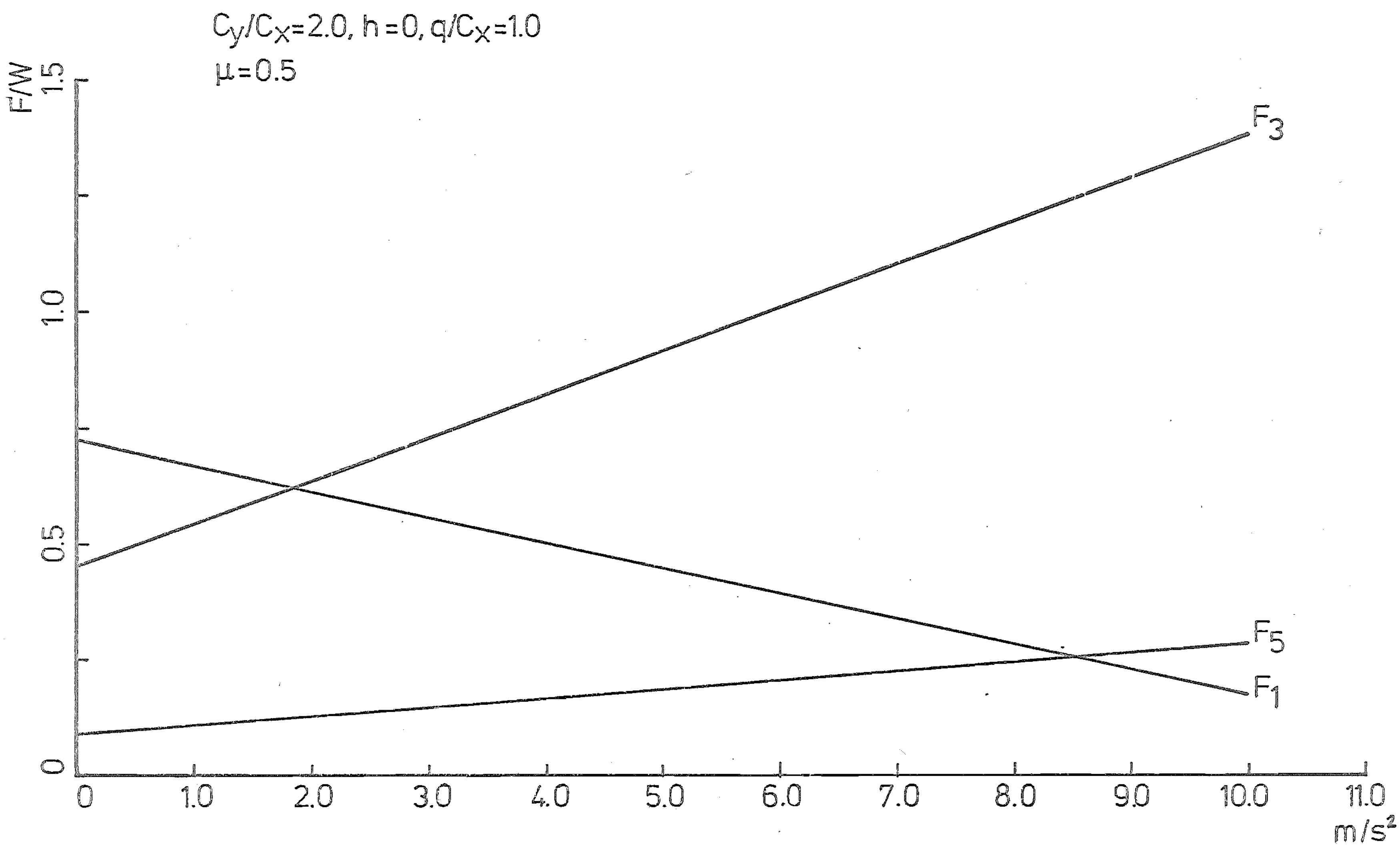
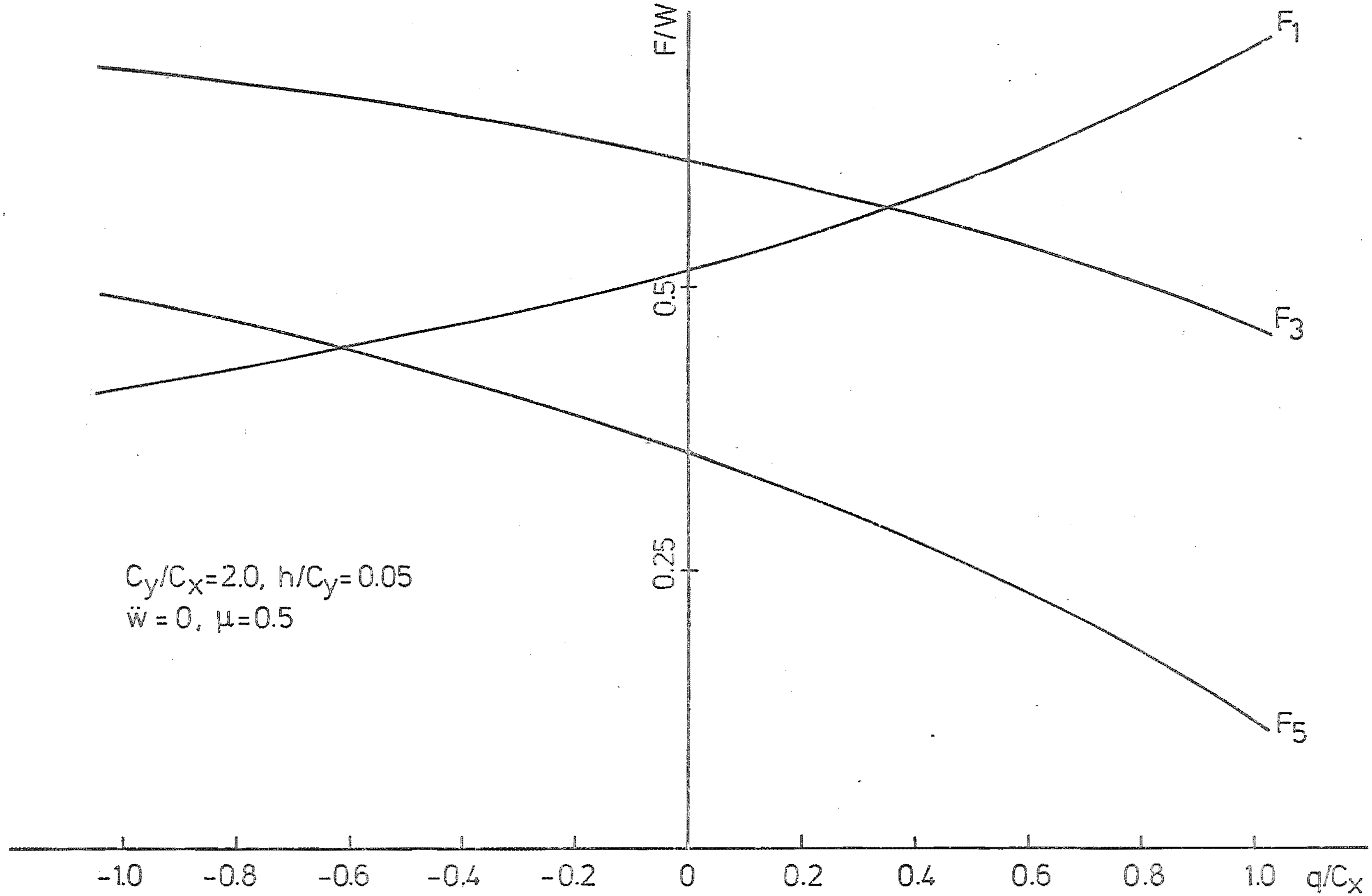


FIG. 10.11 TIPPED BLOCK IN PLANE SLIDE

CONTACT NORMAL FORCES vs HOLE PLANE CONTACT POSITION (q)



Also of interest are the effects of the variables plotted in Figures (10.7 - 10.10):

Figure 10.7 shows the effect of block geometry (C_y/C_x) variations on the contact normal forces.

Figure 10.8 shows the effect of the block weight (W) variations on the contact normal forces. The relationship is linear.

Figure 10.9 shows the contact normal forces plotted against the confine position - a function of h. As h is increased, the confine contact forces are correspondingly increased and this, for positive (upwards) frictional forces, has the effect of reducing F_1. Conversely, F_1 is increased for negative μ_3 and μ_5 values. An untipped slide can be achieved by using large negative h values.

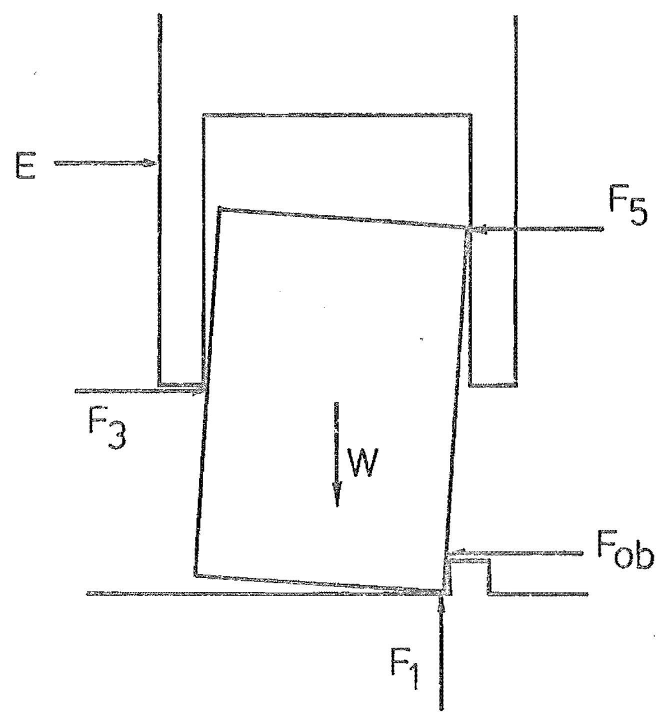
Figure 10.10 shows the effect of lateral acceleration on the contact normal forces. There is a linear relationship here. For positive μ_3, μ_5 values, F_1 is decreased due to the enhanced lifting effect of the increased F_3, and F_5; the converse is true.

Reference to the model in Figure 10.4 will show that if the point of hole plane support, S, is shifted due to the interception of the hole perimeter, then the value of q will vary. The distance q, may take values defined by -

$$-C_x < q \leqslant C_x \tag{10.21}$$

when $q = -C_x$ the block has either contacted the chamfer surface if one exists, or has entered the hole. Figure 10.11 shows the contact normal forces plotted against the hole plane contact position as defined by q. Obviously, the confine contact normal forces F_3 and F_5 increase for a decrease in q (for both positive and negative μ_3, μ_5 values).

FIG.10.12 OBSTACLE CONTACT



It is important to note that the expressions for F_1, F_3, F_5 give the contact forces on the block, as an external effort accelerates the system by $\ddot{x}$. Of course in steady state motion $\ddot{x} = 0$, and these forces are correspondingly reduced. If the external effort acting on the block is, say, E, then the following equation holds:

$$E - F_2 - m\ddot{x} = 0 \tag{10.22}$$

given that E acts in the x direction. In the tipped mode, Equation (10.9) is applicable, so the relation :

$$E = F_3 - F_5 \tag{10.23}$$

is derived.

The event of the block being resisted by an obstacle is covered by Equations (10.9 and 10.11), but the new conditions are :

$$\ddot{x} = \ddot{y} = \ddot{\theta} = 0 \tag{10.24}$$

$$\text{and } E = F_3 - F_5 = F_{ob}$$

where F_{ob} is the resisting force of the obstacle, equal in magnitude to the driving effort, E, if motion is absent. See Figure 10.12.

Ignoring frictional forces which are now, in comparison to the applied forces, small. Equations (10.9 - 10.12) become :

$$\begin{aligned} F_3 - F_5 &= F_{ob} = E \\ F_1 &= W \\ -F_1 C_x + F_{ob} C_y &+ F_3 h - F_5 C_y = 0 \end{aligned} \tag{10.25}$$

which, upon simplifying, and isolating F_5, gives :

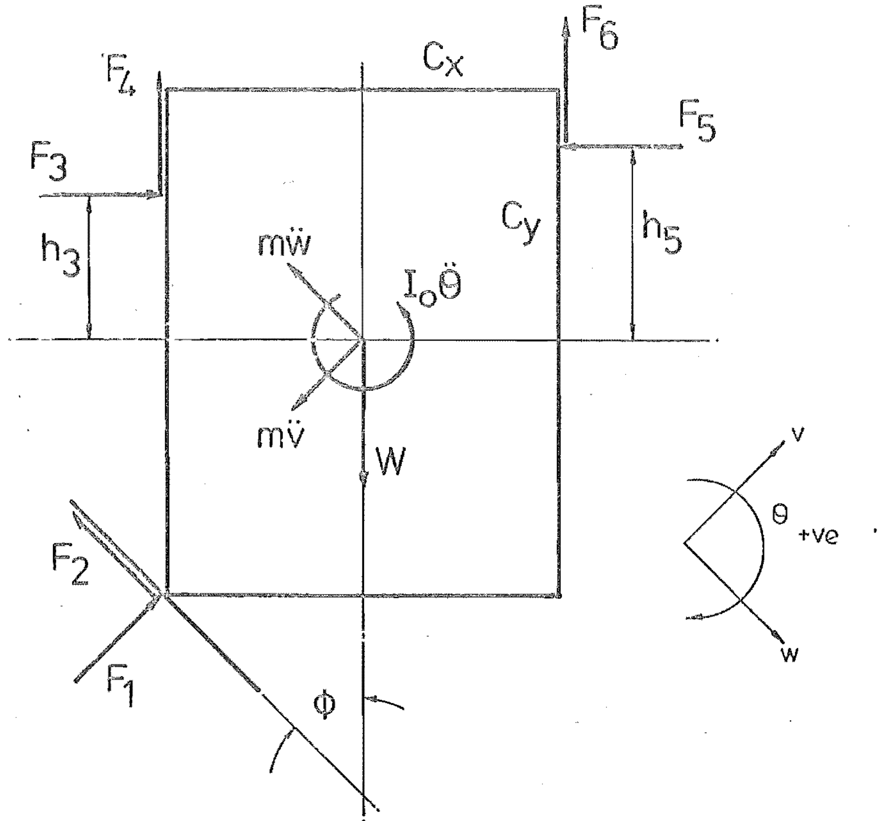
$$F_5 = \frac{W\,C_x - E\,(C_y + h)}{(h - C_y)} \tag{10.26}$$

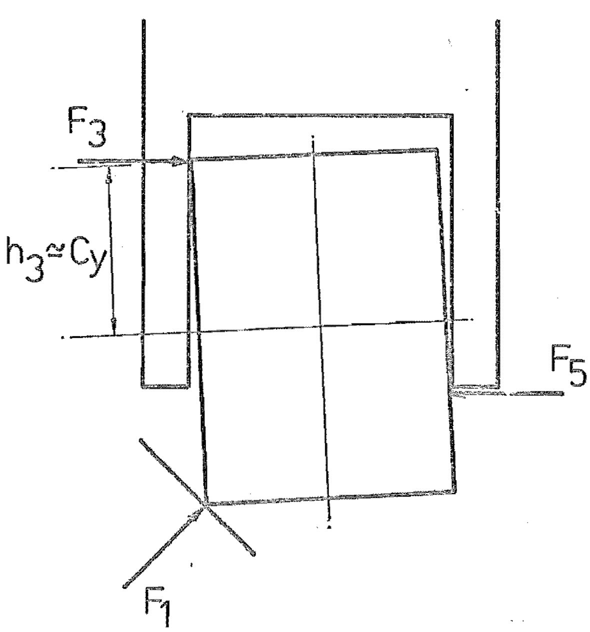
and for F_3, by substituting into Equation (10.25), yielding :

$$F_3 = E + F_5 = E + \frac{W\,C_x - E\,(C_y + h)}{(h - C_y)} \tag{10.27}$$

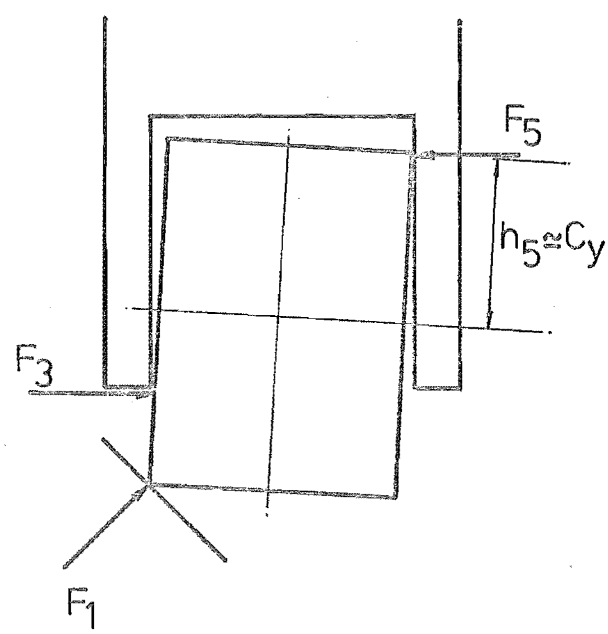
The use of Equations (10.25, 10.26 and 10.27) is to establish an upper limit for the driving effort E, in a manner that the resulting stresses

FIG.10.13 PEG IN CHAMFER SLIDE





a backward lean, $h_3 \simeq C_y$



a forward lean, $h_5 \simeq C_y$

on the block are always below the crushing threshold, to prevent block damage.

Now that the behaviour of a loosely confined block in motion across both the hole plane and the hole perimeter has been examined, and its attitude and the forces acting on it, can be theoretically derived, the investigation will be directed at its mechanics on the chamfer face.

10.3 Peg Behaviour on a Chamfer Face

The examination of the behaviour of the peg, and the resulting forces acting on it when in chamfer face contact, is necessary for the placement strategy in which chamfer effects are used.

The equations to be developed will enable the lateral force on the peg holder (confines) to be derived when an axial force in addition to the peg weight is applied. This net lateral force is used for slaving the manipulator-holder and the peg into alignment and subsequent entry.

This situation is modelled in Figure 10.13. The chamfer surface angle, ϕ, represents either the hole chamfer angle, or the peg chamfer angle; and h_3 and h_5 are the positions of the contact points with the loose confine referred to the peg's minor axis. W is the assembly effort.

Resolving the forces in the w, v, and θ directions of the co-ordinate system shown, the equations of motion are :

$$\Sigma F_w = -F_2 - F_4\cos\phi + F_3\sin\phi - F_6\cos\phi - F_5\sin\phi + W\cos\phi - m\ddot{w} = 0 \quad (10.28)$$

$$\Sigma F_v = F_1 + F_4\sin\phi + F_3\cos\phi + F_6\sin\phi - F_5\cos\phi - W\sin\phi - m\ddot{v} = 0 \quad (10.29)$$

$$\Sigma M_o = F_1\sin\phi C_x - F_1\cos\phi C_y + F_2\cos\phi C_x + F_2\sin\phi C_y + F_3h_3 + F_4C_x - F_5h_5 - F_6C_y - I_o\ddot{\theta} = 0 \quad (10.30)$$

Now, the motion of the peg is down the chamfer face, and rotation of the peg is limited by the close confine; therefore :

$$\ddot{v} = \ddot{\theta} = 0$$

Also, the peg is dropping from the confine as it moves down the chamfer face; therefore, the frictional forces are acting at their upper limits, so :

$$\begin{aligned} F_2 &= \mu_1 F_1 \\ F_4 &= \mu_3 F_3 \\ \text{and } F_6 &= \mu_5 F_5 \end{aligned} \qquad (10.31)$$

There are three equations (Equations 10.28, 10.29 and 10.30) relating the three unknowns F_1, F_3 and F_5. Upon substitution and rearrangement, the following contact normal force expressions are obtained :

$$F_5 = \frac{m\ddot{w} + W\sin\phi\left(\mu_1 + E\dfrac{(\mu_1 A + C)}{(G - AE)}\right) - W\cos\phi}{(BE + H)\dfrac{(\mu_1 A + C)}{(G - AE)} + B\mu_1 - D} \qquad (10.32)$$

$$F_3 = \frac{F_5(BE + H) - W\sin\phi E}{(G - AE)} \qquad (10.33)$$

$$F_1 = W\sin\phi - AF_3 - BF_5 \qquad (10.34)$$

$$\begin{aligned} \text{where } A &= \mu_3\sin\phi + \cos\phi \\ B &= \mu_5\sin\phi - \cos\phi \\ C &= \sin\phi - \mu_3\cos\phi \\ D &= \sin\phi + \mu_5\cos\phi \\ E &= \sin\phi C_x - \cos\phi C_y + \mu_1\cos\phi C_x + \mu_1\sin\phi C_y \\ G &= h_3 + \mu_3 C_x \\ H &= h_5 + \mu_5 C_x \end{aligned} \qquad (10.35)$$

Again from these expressions it is found that

$$\begin{aligned} F_5 &= f_4(\ddot{w}, \phi, \mu_1, \mu_3, \mu_5, h_3, h_5, m) \\ F_3 &= f_5(\quad " \quad " \quad " \quad " \quad) \\ F_1 &= f_6(\quad " \quad " \quad " \quad " \quad) \end{aligned}$$

FIG. 10.14 BACKWARD LEANING BLOCK IN CHAMFER SLIDE
CONTACT NORMAL FORCES vs FRICTIONAL COEFF.

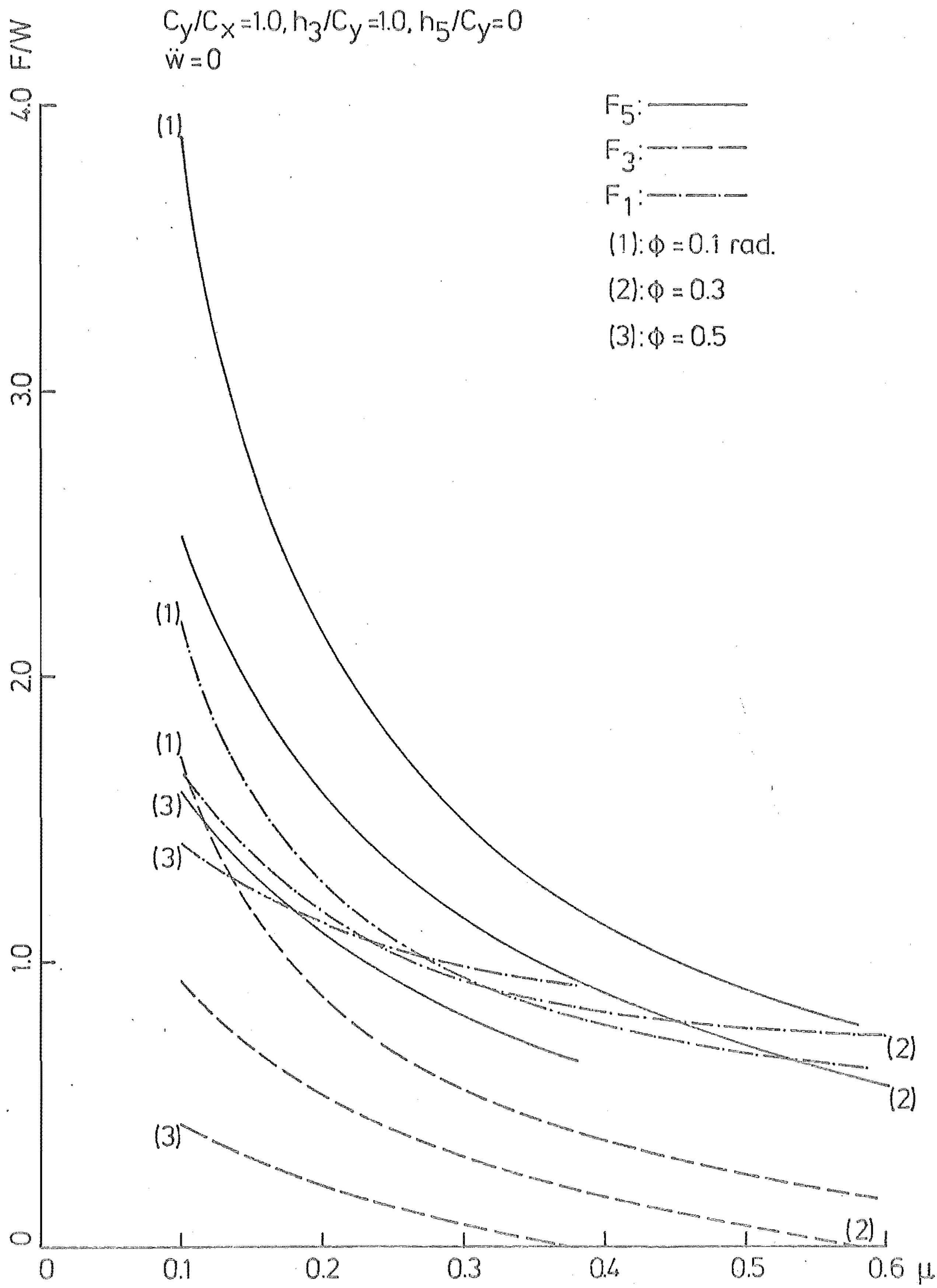


FIG. 10.15 BACKWARD LEANING BLOCK IN CHAMFER SLIDE

CONTACT NORMAL FORCE vs CHAMFER SLOPE

$C_y/C_x = 2.0,\ h_3/C_y = 1.0,\ h_5/C_y = 0$

$\ddot{w} = 0,\ \mu = 0.1$

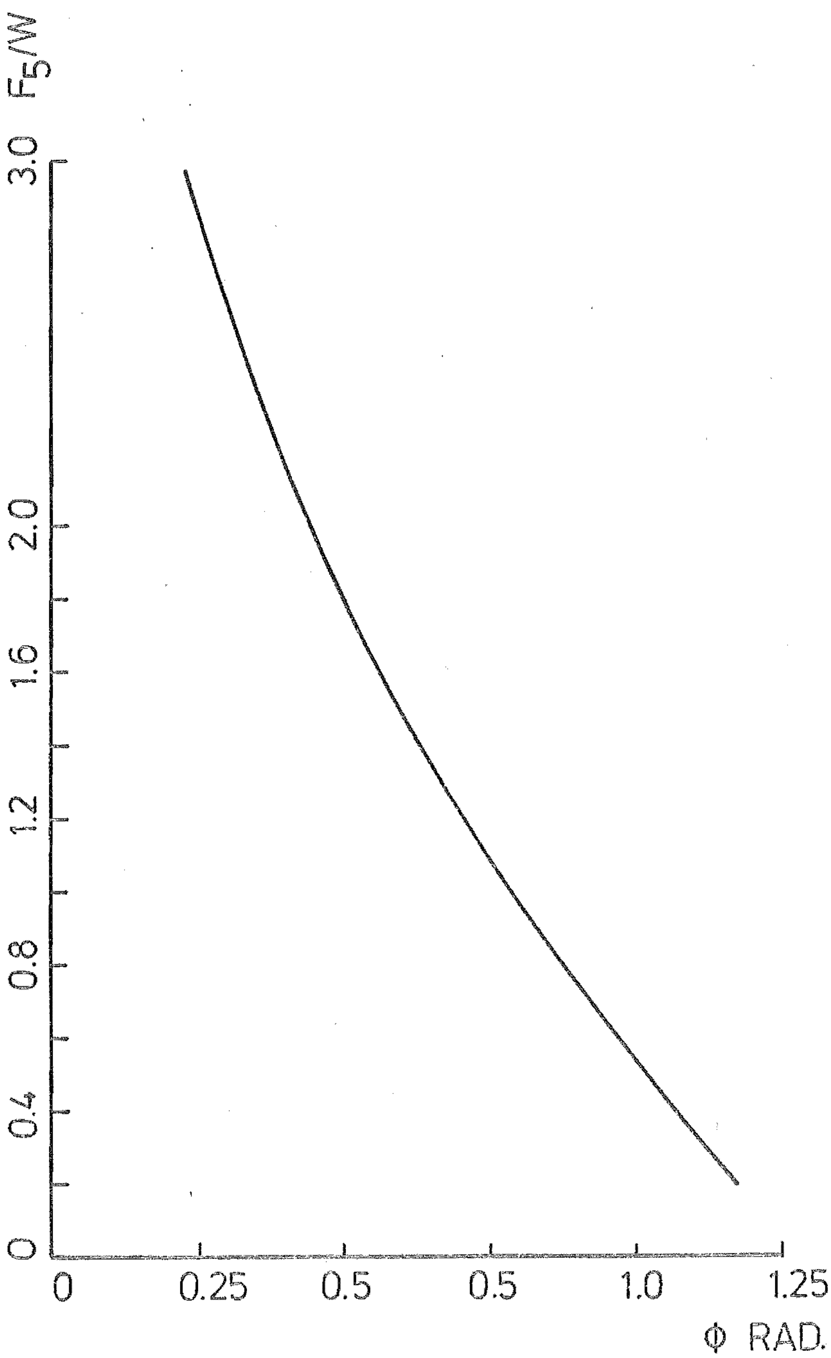


FIG.10.16 BACKWARD LEANING BLOCK IN CHAMFER SLIDE

CONTACT NORMAL FORCES vs AXIAL FORCE

$C_y/C_x = 2.0$, $h_3/C_y = 1.0$, $h_5/C_y = 0$

$\ddot{w} = 0$, $\mu = 0.1$, $\Phi = 0.5$ rad.

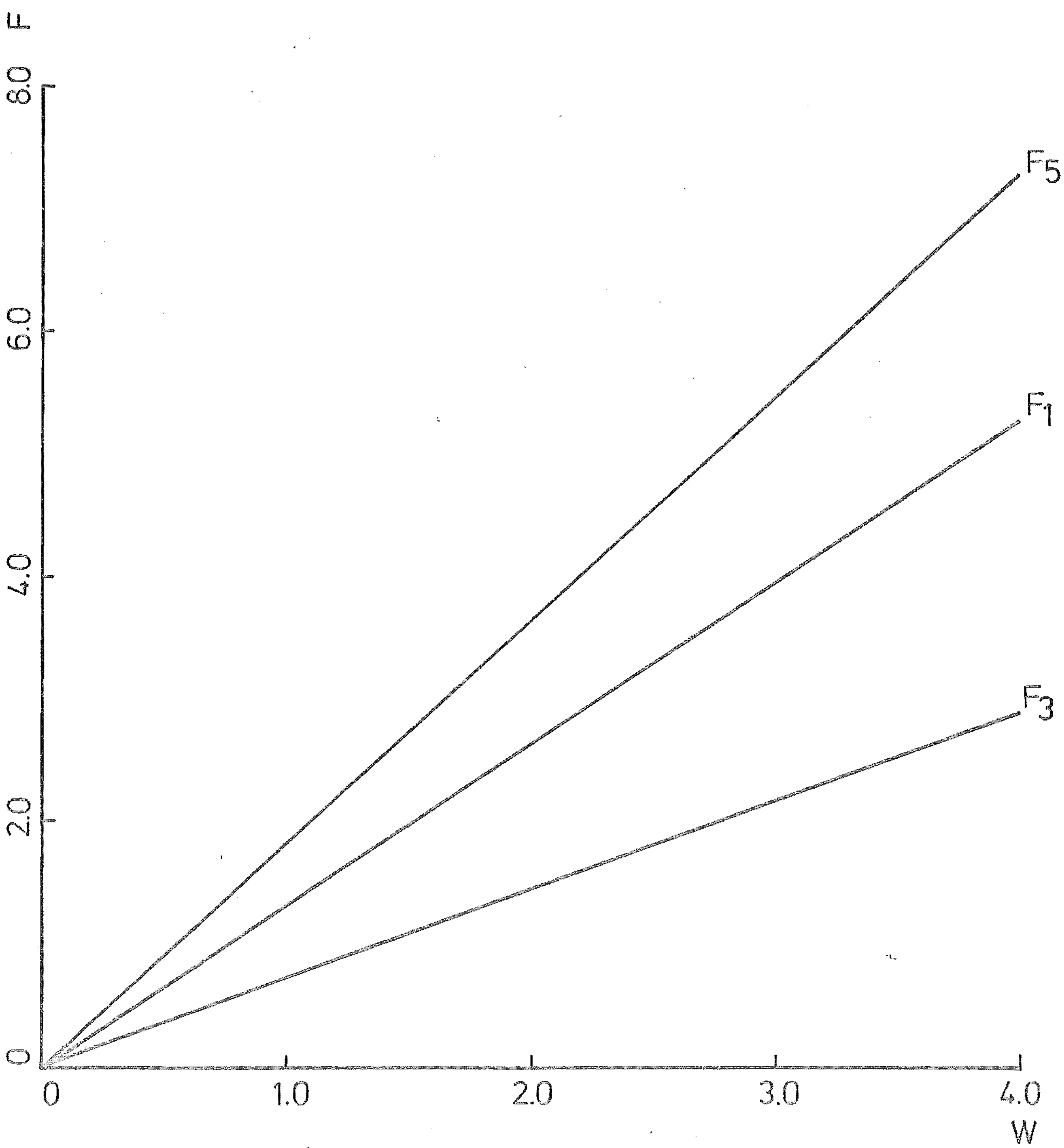
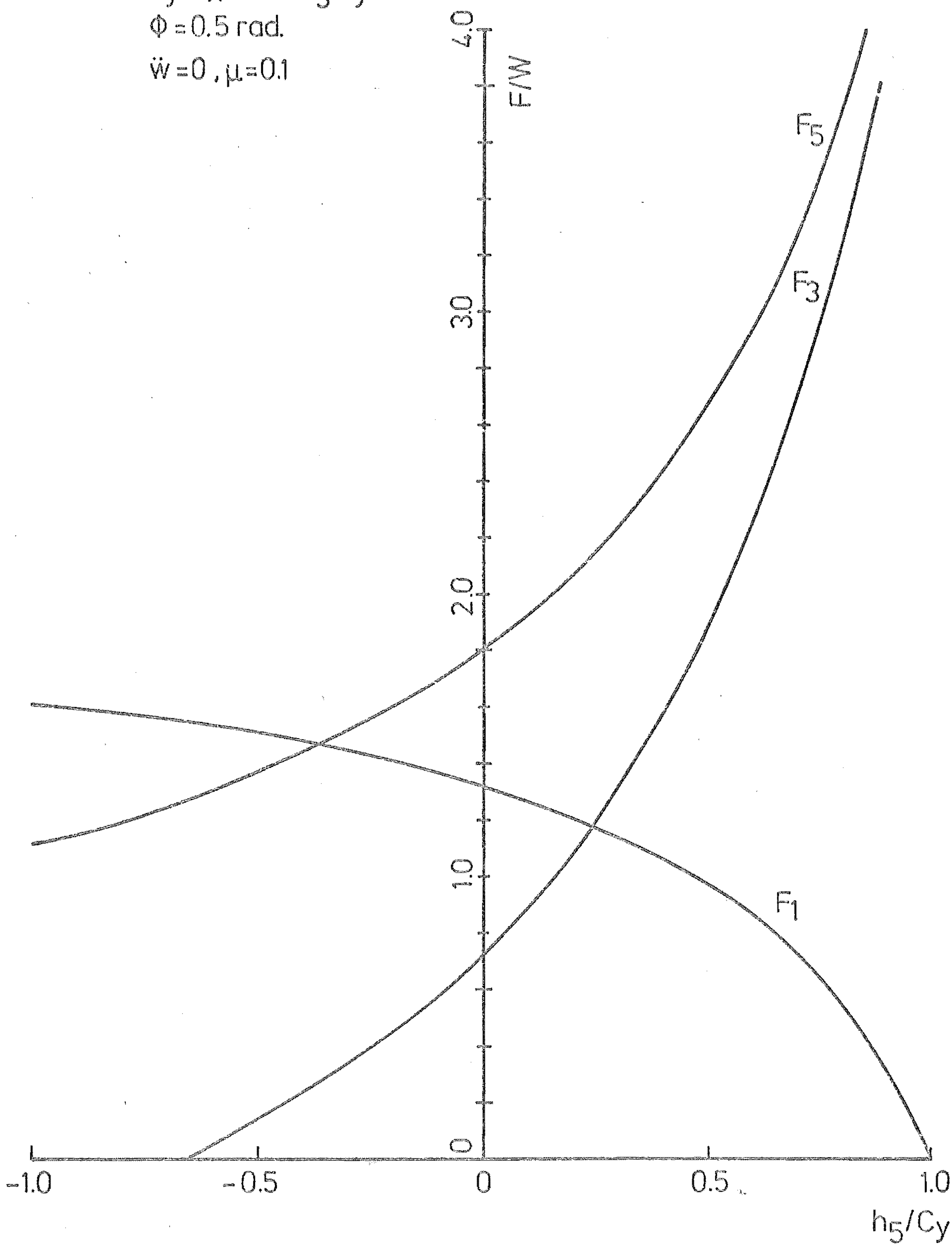


FIG.10.17 BACKWARD LEANING BLOCK IN CHAMFER SLIDE

CONTACT NORMAL FORCES vs CONFINE POSITION (h_5)

$C_y/C_x = 2.0$, $h_3/C_y = 1.0$
$\Phi = 0.5$ rad.
$\ddot{w} = 0$, $\mu = 0.1$



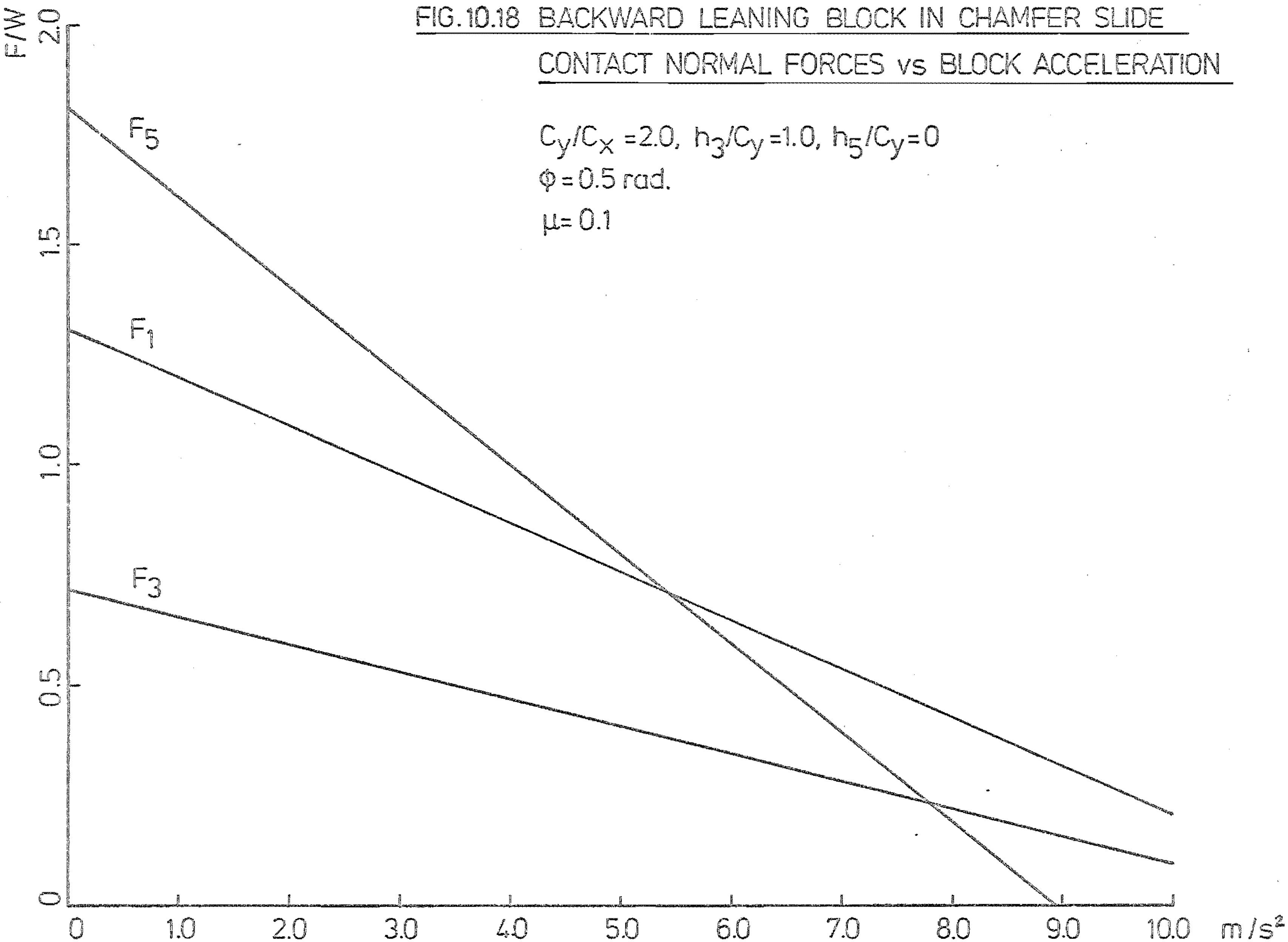


FIG.10.18 BACKWARD LEANING BLOCK IN CHAMFER SLIDE
CONTACT NORMAL FORCES vs BLOCK ACCELERATION

Figures 10.14 - 10.18 will now graphically show the relationship between the contact normal forces F_1, F_3 and F_5 and the different variables.

The backwards leaning attitude of the block (see Figure 10.13), where $h_3 = C_y$, is the most probable block orientation for most chamfer conditions. Therefore, in Figure 10.14, this block attitude is assumed for calculating F_5 in Equation (10.32); the subsequent plotting of values has indicated this assumption to be correct. Figure 10.14 shows the variation of F/W with μ ($\mu_1 = \mu_3 = \mu_5$), and ϕ. Positive contact normal force values indicate a backwards leaning block. Note that an increase of μ, or a decrease in chamfer slope (increase in ϕ) reduces F_5 and F_3.

To show that the effect of change of chamfer slope, ϕ, on F_5 is non-linear is Figure 10.15.

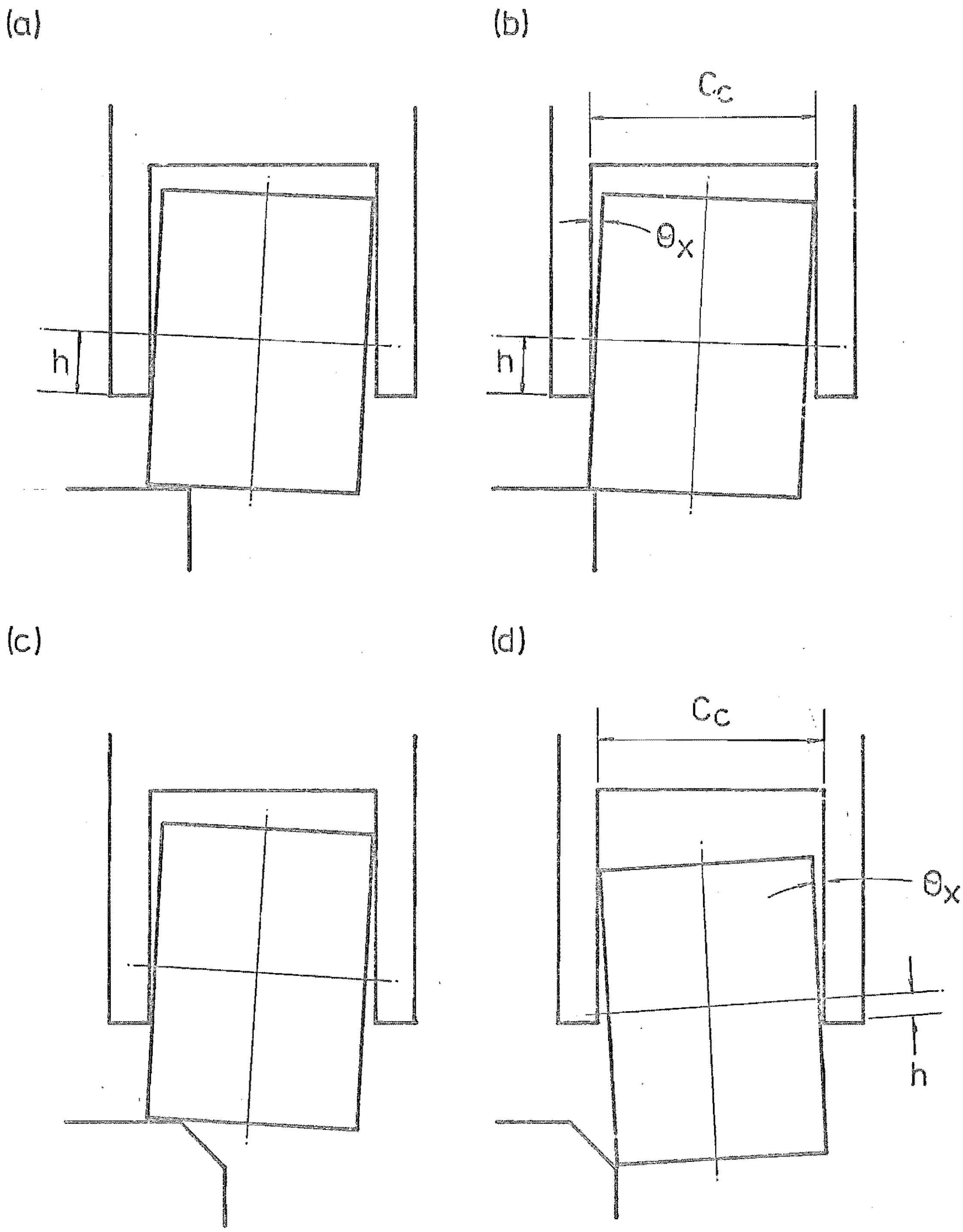
Figure 10.16 shows the effect of variations in the axial force, W, on the contact normal forces. The relationships are linear.

Figure 10.17 shows the relationship between the contact normal forces and the range of h_5 values. As the block moves down the chamfer, the value of h_5 will of course increase and the forces will change as indicated (whilst in the domain of the model).

Figure 10.18 shows the effect of acceleration, $\ddot{w}$, on the contact normal forces. Force reduction is due to the approach to the unconfined block-sliding-on-chamfer condition. In practice the $\ddot{w}$ values will be small.

Now that the effect of the various parameters on the magnitude of the contact normal forces has been examined, it can be seen that any desired block sliding attitude, and within that any range of force magnitudes, can be designed by choosing the appropriate set of parameters.

FIG.10.19 LOOSE CONFINE SIZE : MAXIMUM TIPPED ANGLE



Thus, for each situation the lateral force on the manipulator confines can be determined through

$$F_{lateral} = F_3 - F_5 \tag{10.36}$$

This force will serve to eliminate the radial misalignment between the peg and hole and bring about entry.

The manipulator confine size, or 'looseness' of the loose confinement, is upper bound by the maximum allowable angular misalignment as determined by the jamming criterion (see Chapter 5). As will be recalled, for a particular peg geometry ratio, friction factor, and hole clearance, a gravity assembled peg is allowed up to a particular angular misalignment at the onset of entry (placement Phase II) as determined by the theoretical model on jamming. Here, under loose confinement manipulation, for entry to be successful, this angular alignment envelope must not be violated. Therefore, the peg when under maximum angle conditions (in loose confinement) must still fall within this envelope. Each of the unchamfered, and chamfered, modes, will now be examined. Figure 10.19(a) and (b) shows the peg in the unchamfered mode of operation. Here, obviously, the condition of maximum angle is depicted in Figure 10.19(b). The magnitude of the maximum angle, θ_x, attainable under the confine, is a function of h, C_y/C_x, and the confine diameter, C_c. The relationship exists -

$$\sin\theta_x = \frac{C_c - 2C_x\cos\theta_x}{C_y + h}$$

which, upon rearrangement, gives :

$$h = \frac{C_c - 2C_x\cos\theta_x}{\sin\theta_x} - C_y \tag{10.38}$$

From Equation (10.38) for given C_y, C_c, C_x values, and a known θ_x value, the h value can be obtained. It was found that for successful entry θ_x must be less than the maximum angular misalignment as permitted by the jamming criterion. This then gives the maximum value for θ_x, which when substituted in Equation (10.38) gives the maximum value of h. For the illustrated situation $h_3 = -h$.

In the chamfered mode of operation, shown in Figures 10.19(c) and (d), the maximum angle condition is depicted in Figure 10.19(d). The maximum value for h is also given by Equation (10.38). Note that the maximum h value occurs just before entry - at the lowest point of chamfer contact. Here $h_5 = -h$.

In conclusion, the application of this loose confinement mode of manipulation awaits the development of an accurate and efficient search strategy.

CONCLUSION TO PART TWO

In Part II of this thesis the phenomenon of body contact was examined. It was envisaged that the contact between the assembly components would provide information that was usable to derive the state of relative alignment between the contacting components.

More specifically, a one-to-one correspondence between a sensed reaction and a misalignment state was sought. This would enable a solution system of the desired mechanical sophistication to be realised.

However, a deeper investigation into the possibility of the use of tactile feedback revealed that, in general, there is poor correspondence between the general component misalignment and the felt contact reaction. In certain contact forms - say the restricted peg edge-hole plane, or the peg edge-hole chamfer face cases there is a direct relationship between the alignment state and the contact reaction. Since a peg assembling into a hole may experience the entire range of contact forms, each with different, or perhaps no relationship between alignment state and felt reaction, a general single contact tactile method of sensing was not attained.

Also examined were the mechanics of chamfers, the result of which could be used to optimise its design. But again, this involves but one of many contact zones and is usable as the sole mechanism for implementing placement Phase I only if chamfer contact is guaranteed each time a peg is placed towards a hole. However, the realisation of this restriction using the currently available technology conflicts with the envisaged solution system.

Another technique investigated for its anticipated usefulness as a facet of a solution system was loose confinement manipulation. This concept attempts to use the sympathetic contact forces generated in peg-hole contact to achieve peg entry automatically.

It will be realised that the investigated areas so far will provide solutions in specific regions of interaction during placement Phase I and cannot be extended beyond these to envelope the whole placement problem.

However, it is entirely possible that the information derived from the above studies, and their respective solutions, may be combined, and perhaps remoulded into a total solution system to the assembly problem of placement. This is the subject of Part III.

P A R T   T H R E E

SOLUTION SYSTEMS

INTRODUCTION TO PART THREE

In Part II the possibility of using the felt contact force between component parts being assembled to give an indication of the state of mis-entry was considered. It was found, however, that only certain contact forms produced usable correlations between contact reaction and general peg-hole misalignment. This, of course, is inadequate for a sensing system that is to operate over the entire placement Phase I operation with its many possible contact forms.

What is now sought is an entire solution system that can cope with all the possible contact forms encountered, sensing and correcting the misalignment within each zone, culminating with a successful entry. This solution will be essentially tactile in character, fitting in with the theme of this investigation, and is likely to use information derived from the theoretical analyses of Part II.

Essential information to bear in mind in this hopefully creative section are the thoughts on assembly placement - Phases I and II, the outline of the posed problem (Part II, Introduction), and the type of solution system sought (Chapter 6).

CHAPTER ELEVEN

SOME TACTILE SOLUTIONS

11.1 Introduction

The solution systems considered here are aimed at the assembly placement phases. This area, as already discussed, is the most demanding stage of the assembly operation and at the moment, remains the elusive link that is still required for a complete solution to the problem of flexible automatic assembly.

As this study is an examination of the phenomenon of body contacts in assembly situations, and subsequently derived topics, the proposed solution systems reviewed draw heavily from the material discussed in Parts One and Two.

The solution proposals fall broadly into two categories - one involving the use of something extraneous to the assembly; that is, an assembly aid, and the other, using only the assembly components themselves. Assembly aids solutions are reviewed first (Sections 11.2 - 11.5) and are followed by those (Sections 11.6 - 11.8) falling into the second category.

These proposals are discussed briefly in concept only without the inclusion of technical details; however, all the functions involved are technically realisable.

11.2 The Variable Funnel

The concept of a funnel is used in this solution to achieve linear alignment in placement Phase I. The entry mouth of the funnel is large enough to accommodate the maximum alignment error foreseen for the handling arm, and this funnel is centred on the hole.

FIG. 11.1 THE VARIABLE FUNNEL

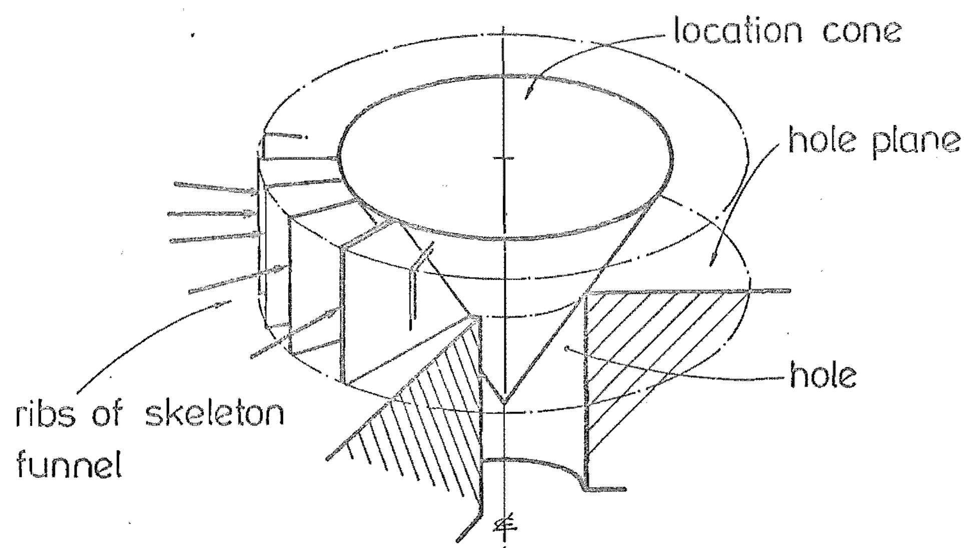
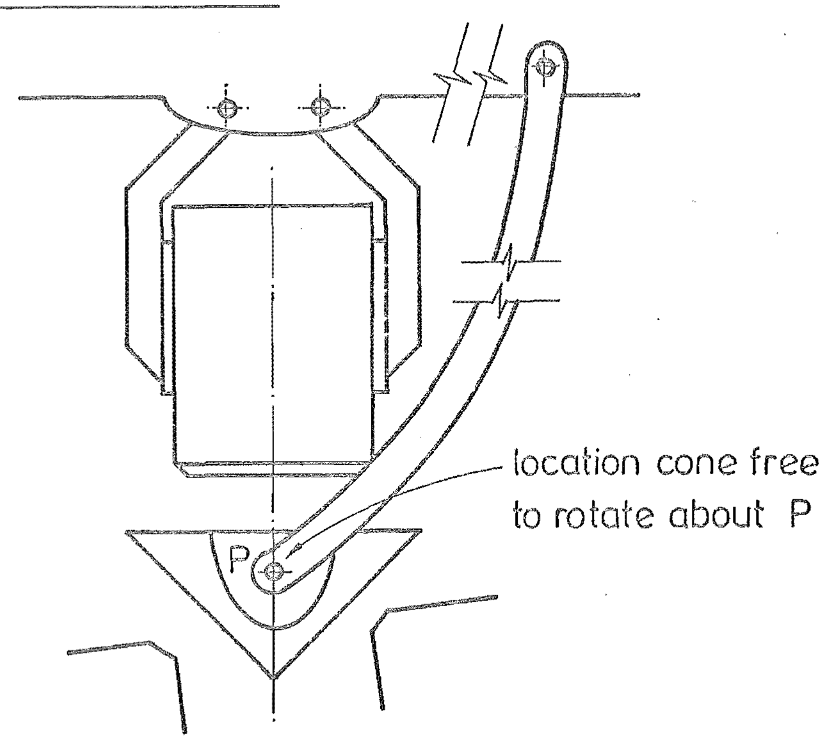
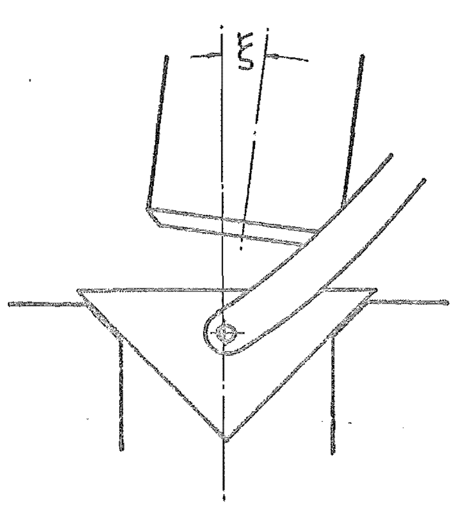


FIG. 11.2 HAND LOCATION CONE

(a)



(b)



For locating the funnel, a 'location cone' is lowered into the hole; this cone is flexibly held such that complete hole contact is made - see Figure 11.1. The allowable error for the successful deposit of this cone is ± the hole radius - for typical applications this should be more than adequate. In effect, the allowable assembly misalignment error is increased by the use of the location cone. Ideally, from a quantity that is not acceptable, to one that is, to the mechanical transfer component. Once located, the cone is used to align a skeleton funnel and then withdrawn. This funnel now serves as a generous temporary chamfer for placing the peg.

The peg upon being lowered will make peg edge/hole chamfer face contact. As already discussed in Chapter 8, if there is assurance that there is only one contact form to be encountered, then angular alignment is achievable through simple tactile feedback. So, maintaining an attitude of axial alignment, the peg is slaved off the contact reaction down the chamfer to achieve linear alignment and entry.

To cope with a range of peg-hole sizes, a skeleton funnel is used. The actual design of this funnel would be determined by the judicious consideration of factors like the range of peg sizes and the necessary funnel mouth diameter.

With this system, neither the peg nor the hole has to be chamfered, but a reasonable working area is needed for the operation of the funnel.

11.3 The Hand Location Cone

In this system a cone is located beneath, and aligned to, the gripped peg as shown in Figure 11.2(a). The hand is then lowered towards the hole and freed to be slaved off the contact forces. On achievement of cone/hole contact, as shown in Figure 11.2(b), only

FIG.11.3 FINGER LOCATION CONES

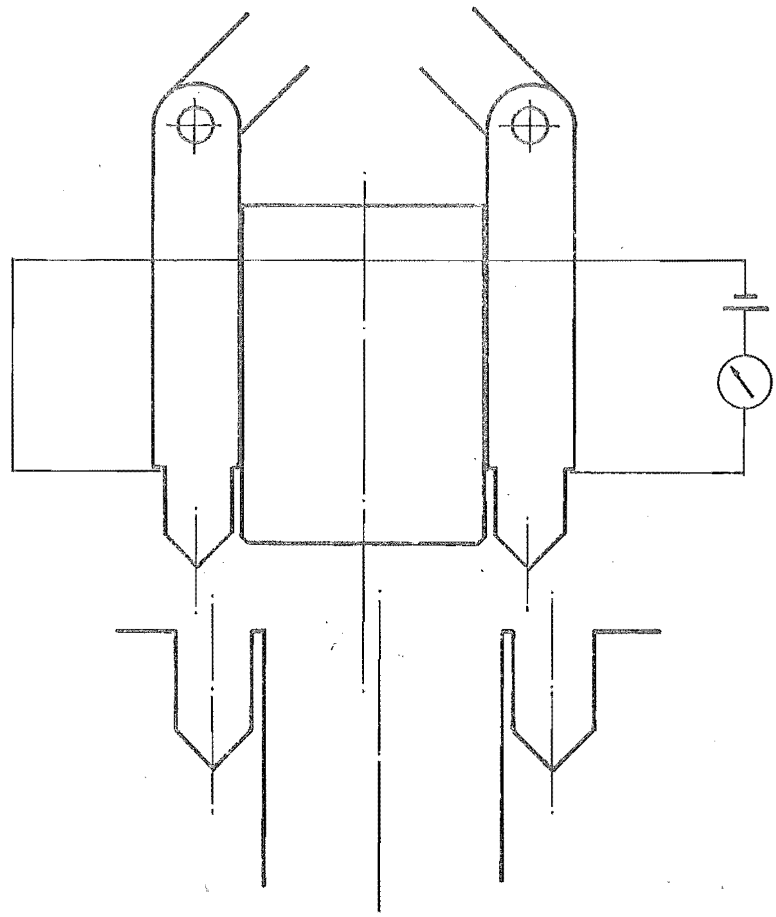
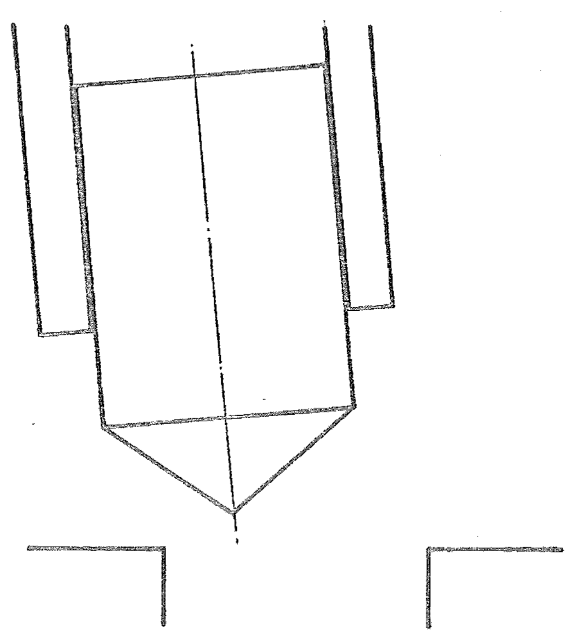


FIG.11.4 FULL CONE CHAMFER



angular misalignment persists; this is subsequently corrected through the monitoring of the angle ξ. Having aligned the peg directly above the hole, the cone is withdrawn and the peg directly assembled, with perhaps the additional aid of small chamfers.

11.4 Finger Location Cones

The preceding solution proposal does appear mechanically cumbersome and in an effort to streamline this, another solution involving a set of location cones is forwarded. If less unwieldy, this solution requires a more constrained set of input conditions.

Figure 11.3 illustrates the principle behind this scheme. On each of the three or four specially designed gripping fingers is a location cone which locates into its designated locating hole on a specific pitch circle around the assembly hole. The necessary diameter of the locating holes is a function of the manipulator positioning accuracy. Final angular alignment can be achieved by ensuring contact of all the location cones by way of circuit completion detection (Figure 11.3).

11.5 Full Cone Chamfer

Another obvious method of achieving location using the chamfer effect is the use of full cone chamfers. The problem here is one of incorporating such an extensive chamfer into the system (operator and product) design.

In Chapter 8 the effectiveness of large chamfers used in conjunction with tactile feedback as an aid to both angular and linear alignment was discussed. The prerequisite condition of confining the contact form to that of edge/chamfer face contact can be realised by, firstly constraining the relative peg-hole placement error to less than the hole radius dimension, and secondly, the use of a full cone chamfer. See Figure 11.4.

The cone chamfer is either incorporated in the parts design, or made collapsable - either chemically or mechanically - perhaps into a useful bonding agent.

11.6 Invariant Planes Contact

The basic problem lies in the assembly of a peg that is presented in some random position and orientation with respect to the hole. It has to be translated and orientated into the assembled position.

From the analyses of reaction directions of various forms of peg-hole contact, it seems that without the previous knowledge of the relative position of the peg and hole, a sensed reaction force direction is, in general, meaningless. That is to say, there is no unique relationship between the sensed reaction and the general relative alignment, for quite different misalignment forms can result in the same peg sensed contact force. Therefore, there is not to be found general programmed corrective actions that can be taken when a certain reaction is felt.

So, it seems that it is necessary to tie the peg and hole together somehow - to relate one to the other. One method is contact through two defined surfaces, enabling the establishment of an absolute orientation between the two components. For example, the peg face plane and the hole plane are two convenient surfaces, but each will have to be invariantly located with respect to the respective axes.

Therefore, the establishing of contact of these two invariantly orientated planes reduces the problem from a three-dimensional one to one of two-dimensional, or planar, searching.

Once invariant planes contact is achieved, on-plane search techniques can be used to detect the relative direction of the hole, and the radial misalignment duly eliminated.

A method of hole detection, when the peg overlaps the hole, involves the rotation of a calibrated tipping moment that lies in a peg radial plane, about the peg vertical axis, thus sensing a direction of susceptibility to tipping. This direction, of course, is the direction joining the peg and hole axes; motion along this will effect alignment.

11.7 Multiple Contact Tactile Sensing

This is a method of sensing through tactile feedback that uses multiple contacts to gain information about an environment. Each contact reveals the nature of the interacting geometry at that point, and so, a multiple of contact points can be assembled to 'recreate' an outline of the gross interacting geometric shape. Thus, the knowledge of the exact dispositions of the assembly components will enable corrective measures to be determined and carried out. This method of sensing, however, is necessarily slow and costly, in terms both of assembly and computing time.

11.8 Non-Iterative Search

As opposed to the method of hole search described in Section 11.6, which is iterative in that it detects the hole direction and progresses successfully towards it, the methodsconsidered here are non-iterative; they are not conscious of the hole's presence until the peg drops in.

These are optimised mechanical search patterns designed to cover an area of space most likely to contain the hole[14]. If the hole lies within this searched pattern, it is detected by the peg, partially or fully, dropping into it.

Operation is in this manner: The peg is lowered towards the hole and upon contact is orientated normally to the hole plane by tactile feedback. Now a search procedure is engaged and the peg moved in the search pattern under loose confinement; the search is terminated by hole contact.

The width of the search pattern is a direct function of the possible spread of the peg-hole misalignment, so there will be some point at which this method of placement Phase I solution becomes unfeasible due to the amount of time spent. However, for problems of small misalignments of low spread (std. deviation), coupled with a wise search technique, and a generous hole chamfer, this potentially slower method of solution could be effective as a trade-off against its low complexity.

CHAPTER TWELVE

A PARTICULAR SOLUTION : INVARIANT PLANES CONTACT

12.1 Introduction

The invariant planes contact solution system was chosen for further investigation and development because of its merits in flexibility and potential. Its method of solution and its tactile mode of sensing shows promise for the solution of assembly problems beyond that of cylindrical peg and holes, thus hinting at the eventual possibility of an extended repertoire of solution techniques all related by a similar mode of operation. These tactual techniques (including invariant planes contact for the peg and hole problem) may eventually cover the broad range of assembly problems encompassing rectangular inserts, and multi-hole washers.

The concept will now be briefly recalled, and then examined in detail for implementation. In the interest of clarity, the presentation will be in three sections :

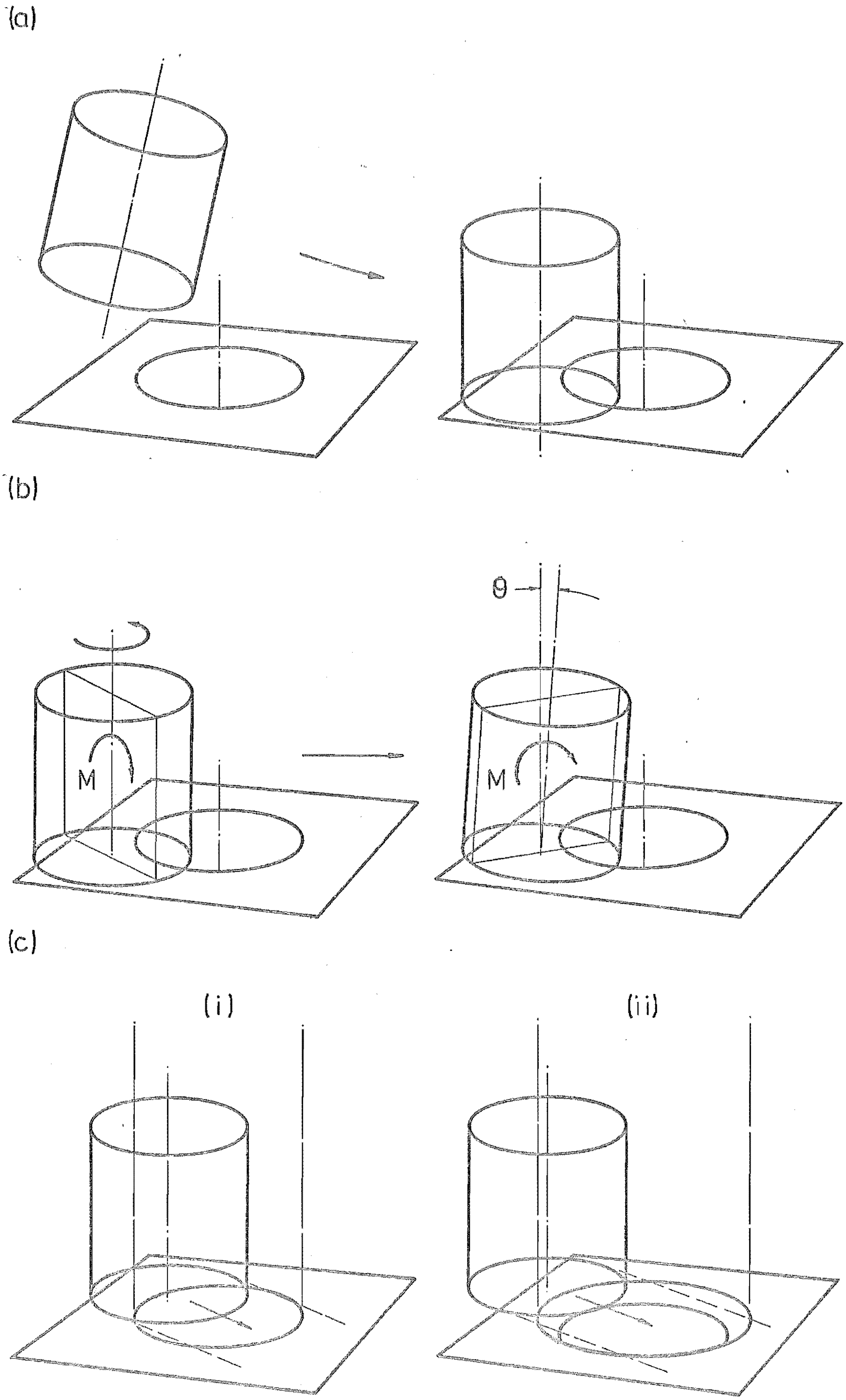
(1) Invariant Planes Contact

In this first step the difficult problem of a generally misaligned peg is simplified to one of a designed misalignment, through the contacting of two invariantly oriented planes. The two obvious planes to use are the peg face plane and the hole plane, both of which are defined normal to the peg and hole axes respectively. Therefore, the contact of these two planes implies axial alignment of the peg and hole leaving only radial alignment to be corrected. See Figure 12.1(a).

(2) On-plane Hole Search

Once the generally misaligned state is reduced to one of radial

FIG. 12.1 INVARIANT PLANES CONTACT



misalignment only, the next step is to define that radial error. If the peg overlaps the hole then the on-plane hole search method of sensing the susceptibility of the peg to tipping can be employed.

Here, a calibrated tipping moment applied in a peg radial plane is rotated about the peg vertical axis - Figure 12.1(b). The contact geometry in the hole direction due to the peg-hole overlap is less able to resist the applied tipping moment, and this registers as a direction of tipping susceptibility. The lack of stiffness in this direction is sensed through the manifested flex or movement. Thus, the direction of the radial misalignment is derived.

(3) Planar Shift

The remaining step is the physical shift to eliminate the radial alignment error. The shift is in the above derived direction, and pending its accuracy the peg will pass through the entry envelope of the hole - Figure 12.1(c).

To eliminate the need of an extra sensor to detect this passage, the peg will be shifted under the condition of 'loose confinement' (see Chapter 11), such that the peg will

(i) drop into the hole; or

(ii) drop onto chamfer contact.

This, of course, terminates the lateral shift and initiates the next appropriate step.

Since it cannot be guaranteed that the hole will be found during the first shift, it seems sensible to limit the shift distance to an arbitrary figure. So that, if the first shift does not achieve entry, the hole direction is searched again and a new shift direction found. In this manner, the technique is convergent (pending on the arbitrary shift distance).

FIG.12.2(a) CONTACT REACTION WHEN $\xi \leq \alpha_f$

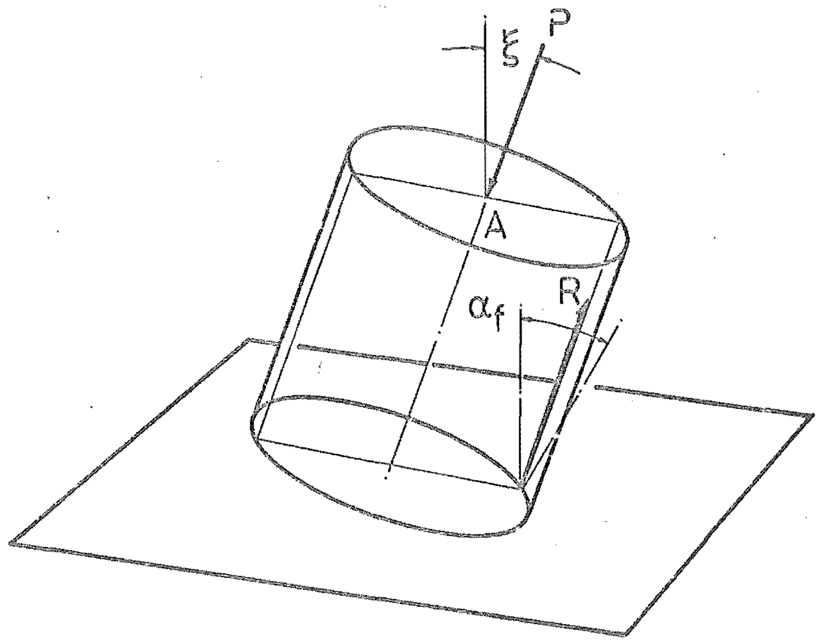
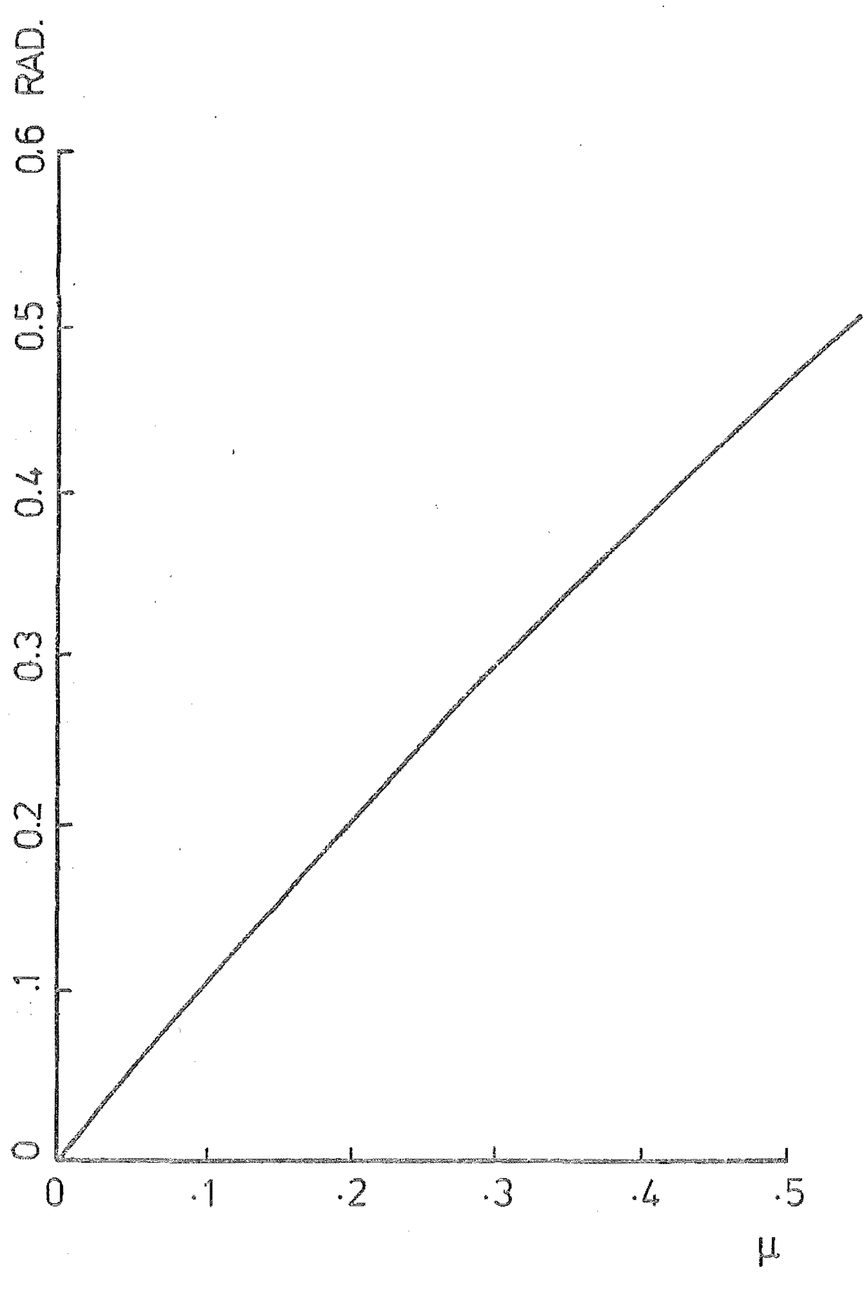


FIG. 12·2(b) ALLOWABLE ANGULAR MISALIGNMENT ($\xi = \alpha_f$) vs. COEFFICIENT OF FRICTION (μ)



Now these steps will be examined in detail and implemented.

12.2 Invariant Planes Contact

The problem in this section is, given a generally misaligned peg and hole, to achieve invariant planes contact. The invariant plane on each is the only defined feature as far as this step is concerned.

It is envisaged that a possible method of solution is through the use of simple tactile feedback; Chapter 8.

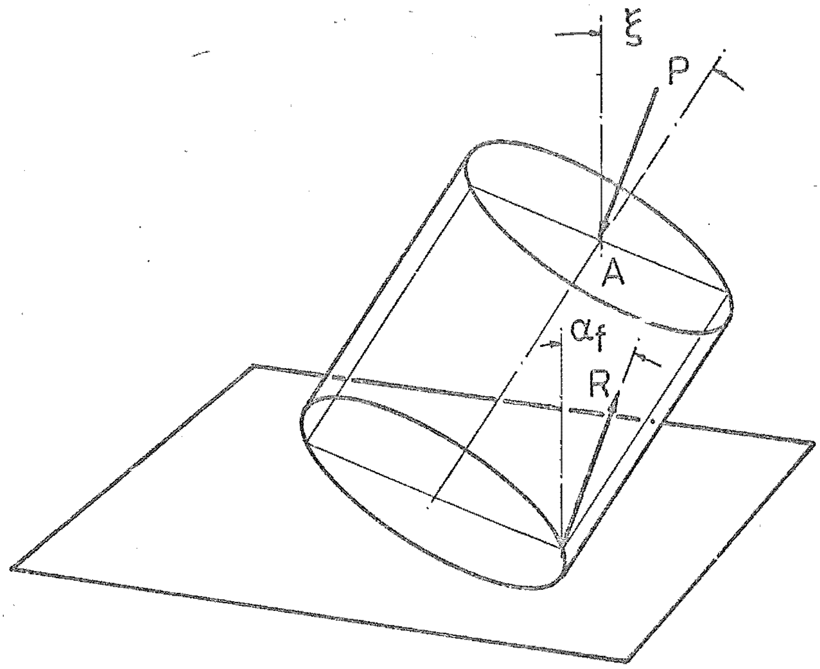
Let these situations of contact be briefly reviewed. It will be remembered that for the contact form of peg edge/hole plane, the peg radial plane of contact contains the angle of maximum angular misalignment, ξ. In addition, if the forcing effort, P, is parallel to the peg axis, all the contact forces lie in this radial plane. See Figure 12.2(a).

When the misalignment angle ξ, is less than the angle of friction, $\alpha_f = (\tan^{-1}\mu)$, the reaction force R is parallel to P, thus generating as sensed at A, a moment M_A, and the forces, axial - F_{AA}, and radial - F_{AR}, such that :

$$\begin{aligned} M_A &= RC_x \quad (\xi \leqslant \alpha_f) \\ F_{AA} &= R \\ R_{AR} &= 0 \end{aligned} \tag{12.1}$$

In this misalignment regime (where $\xi \leqslant \alpha_f$), the magnitude of M_A and F_{AA}, F_{AR}, are independent of the geometry ratio of the peg, C_y/C_x, or ξ. M_A and F_{AA}, F_{AR} lie in the plane containing ξ, and are directed to eliminate ξ (this direction is defined positive). The relationship between allowable ξ and the coefficient of friction μ, such that $\xi \leqslant \alpha_f$ is maintained, is shown graphically in Figure 12.2(b).

FIG. 12.3 CONTACT REACTION WHEN $\xi > \alpha_f$



When the misalignment ξ is greater than the angle of friction α_f, and the peg is restrained from gross movements, the applied force, P, and the reaction force, R, are no longer parallel with the peg axis. See Figure 12.3. Consequently, the moment and forces felt at A are now dependent on ξ, α_f and C_y/C_x, and depending on these factors, their directions can be either positive or negative.

$$M_A = R\cos(\xi - \alpha_f)C_x - R\sin(\xi - \alpha_f)2.C_y \quad (\xi > \alpha_f) \tag{12.2}$$

$$F_{AA} = R\cos(\xi - \alpha_f)$$

$$F_{AR} = R\sin(\xi - \alpha_f)$$

These moment and forces, however, still lie in the maximum misalignment plane.

For a simple tactile feedback solution sensing forces and moments, it is desirable to have a simple consistent correlation between a sensed reaction and the required corrective action. In the case of $\xi \leqslant \alpha_f$, the corrective action as far as alignment is concerned is to rotate <u>with</u> the sensed moment M_A. In the situation where $\xi > \alpha_f$, rotating with F_{AR} is corrective, but rotating with M_A could mean either reducing or increasing ξ, depending on the parameters ξ, C_y/C_x and α_f. There are, however, two methods by which this ambivalence can be overcome:

(i) by constraining angular misalignment such that $\xi \leqslant \alpha_f$;

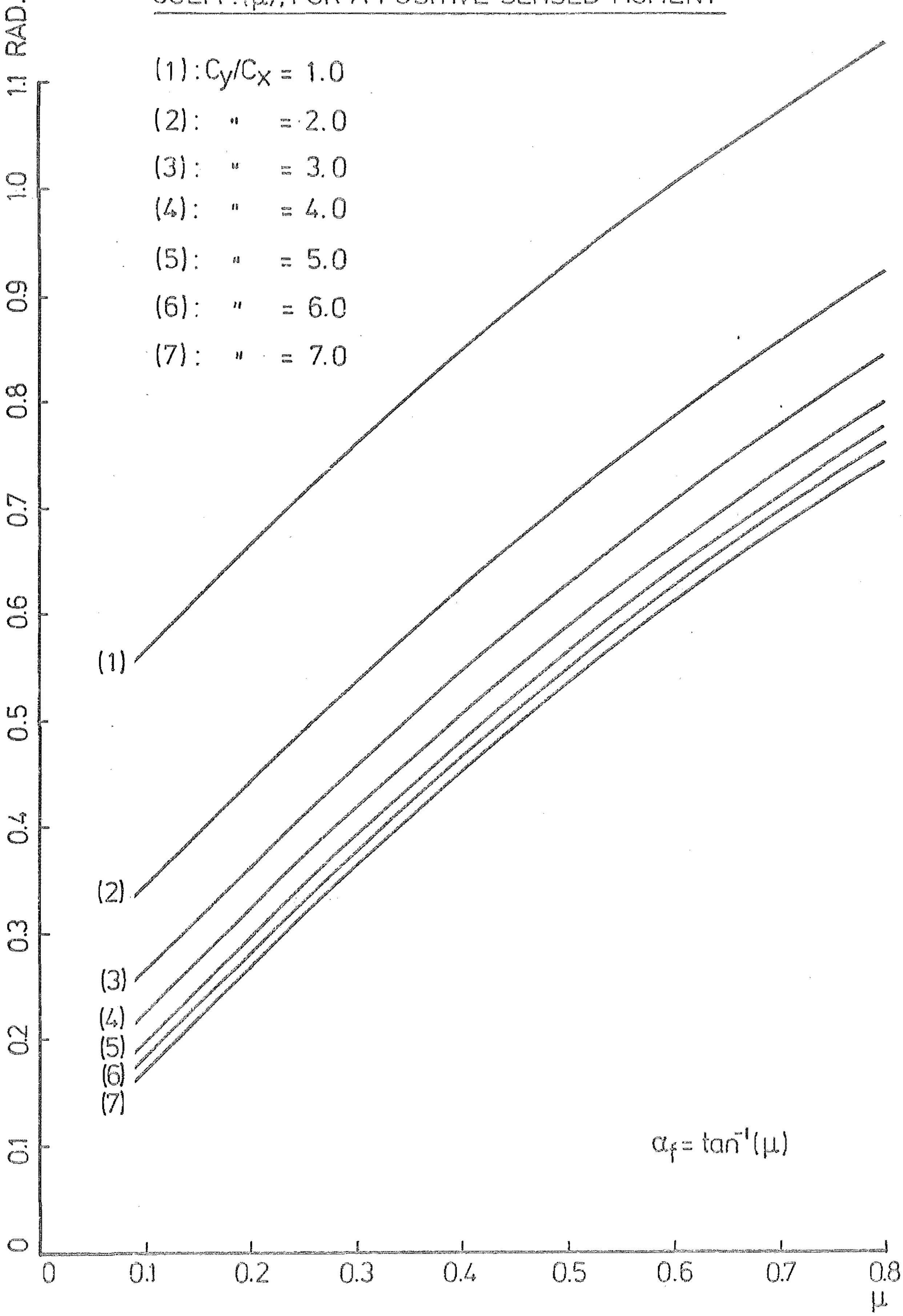
(ii) by manipulating the variables in Equation (12.2) by increasing C_x; that is, for M_A positive, by Equation (12.2):

$$\cos(\xi - \alpha_f)C_x > \sin(\xi - \alpha_f)2.C_y$$

$$\text{i.e.} \quad \tan(\xi) < \frac{C_x\cos\alpha_f + 2C_y\sin\alpha_f}{2C_y\cos\alpha_f - C_x\sin\alpha_f}$$

$$\xi < \tan^{-1}\left(\frac{C_x\cos\alpha_f + 2C_y\sin\alpha_f}{2C_y\cos\alpha_f - C_x\sin\alpha_f}\right) \tag{12.3}$$

FIG. 12.4 GRAPH OF MAX. ANG. MISALIGNMENT (ξ) vs FRICTIONAL COEFF. (μ), FOR A POSITIVE SENSED MOMENT



Equation (12.3) is plotted in Figure (12.4) to show the maximum ξ values corresponding to given C_y/C_x and α_f values. Before deciding on one of these, the other contact forms must be examined.

If the peg-hole combination of concern is that of an unchamfered peg - unchamfered hole (this is the simplest and most basic of the peg-hole combinations), then the other contact form is line/line contact.

The situation of line/line contact between a peg and hole edge has been discussed in Chapters 7 and 8. It was found that the direction of the contact reaction force, R, was confined within the cone of friction centred on the contact normal direction, ON. The direction of ON is defined by the geometry of interaction between the two lines, and is given as

$$\tan\psi = \frac{\cos\beta_h}{\cos\gamma_h} \qquad (12.3)$$

where ψ is the angle between the peg axis and ON, and $\cos\beta_h$ and $\cos\gamma_h$, are the elements of the directional cosine of the hole line segment in relation to the peg. (See Chapter 7). It was also found that the definition of the hole line segment in relation to the peg was insufficient to completely define the gross relative orientation of the peg to the hole. Therefore ψ (and consequently the sensed reaction direction), and the peg-hole misalignment, are <u>not</u> directly related. The values ψ can take range from 0 to $\pi/2$, irrespective of ξ. This limitation of ON to within the peg body i.e.

$$0 \leqslant \psi \leqslant \pi/2$$

however, also implies that when a peg axial initial contact effort is used, the contact reaction R always lies inside the peg body (see Figure 12.5). This, in turn, implies that, at A, is sensed :

(a) a tipping moment, M_A, that can be both sympathetic or non-sympathetic to eliminating ψ;

FIG. 12.5 DIRECTION OF CONTACT RESULTANT wrt THE PEG

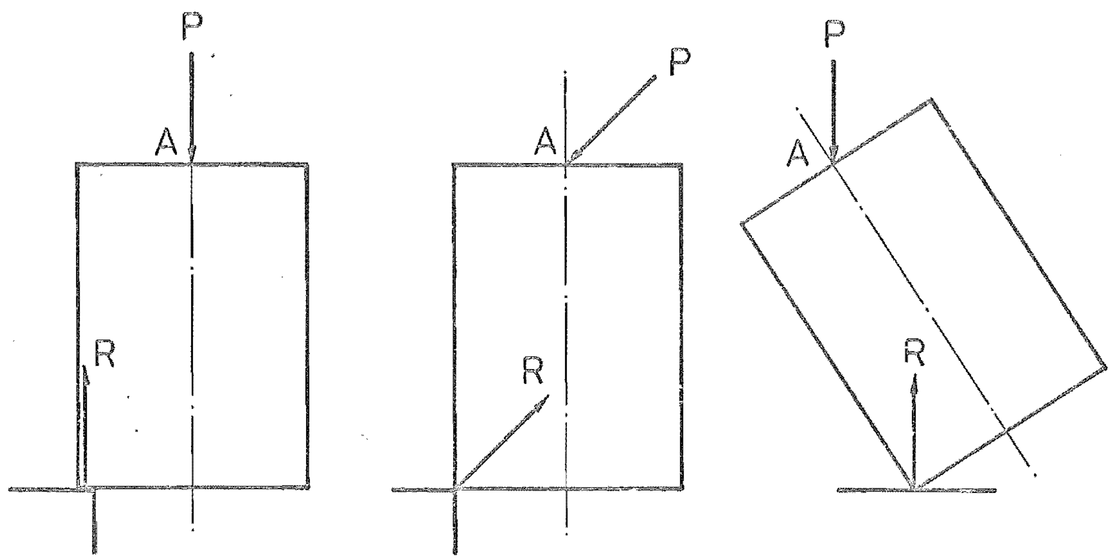


FIG. 12.6 PEG WALL / HOLE EDGE CONTACT

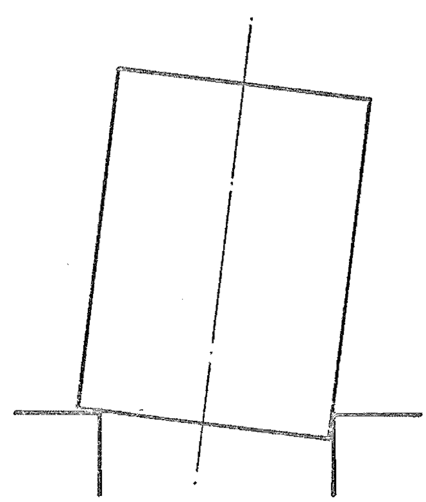
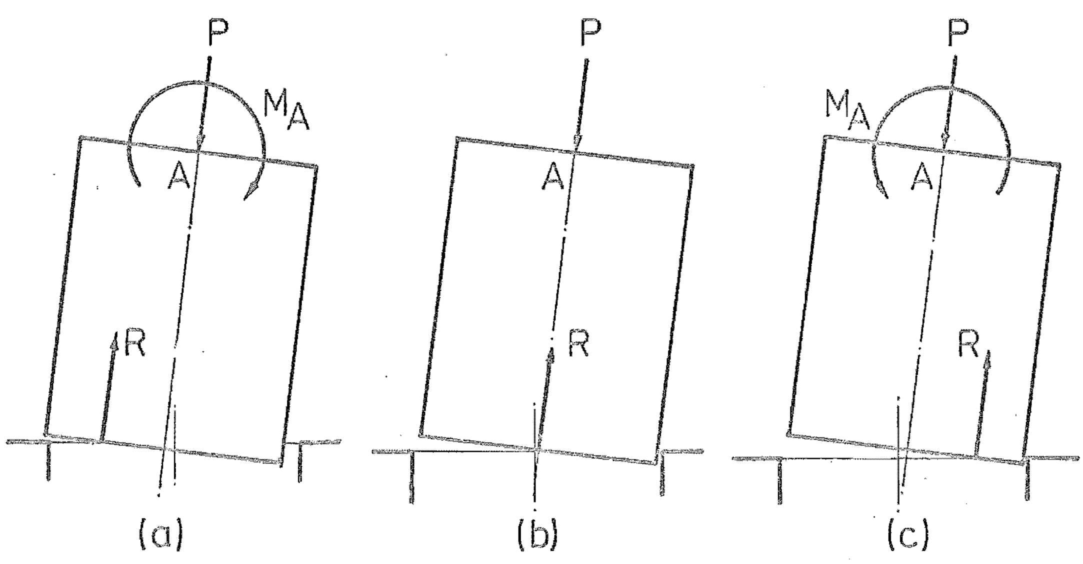


FIG. 12.7 DOUBLE PEG EDGE / HOLE EDGE CONTACT



(b) a peg axial force through A;

(c) a peg radial force, when it exists, always acting in a direction sympathetic to eliminating ψ.

It will be realised that, unlike the situation in hole plane contact, in line/line contacts, ψ does not necessarily lie in the same plane as ξ.

The question of whether correction in the ψ plane will help invariant planes contact now arises. Correction (elimination of ψ) in the ψ plane or sensing plane will either improve alignment by :

(1) Resulting in entry into the hole. This possibility is enhanced if the clearance between the peg and the hole is small and if the initial misalignment is also small.

(2) Resulting in a double peg edge/hole edge contact or deteriorate the existing alignment situation through :

(3) a peg wall/hole edge contact such as that shown in Figure 12.6 which is likely if the peg-hole clearance is large. This situation is undesirable mainly because it introduces another contact mode which, of course, further complicates the problem and reduces the possibility of a simple tactile feedback solution.

Coming back to the double peg edge/hole edge contacts situation (reviewed in Section 8.3.2 which reveals itself to sensors at A, as :

(A) a peg axial force; and

(B) perhaps a moment, M_A, that is again ambiguously related to the peg misalignment ξ, though this time M_A lies in the ξ plane. Figure 12.7 illustrates the types of sensed reactions possible, which shows that following M_A could mean both the improving or worsening of the alignment. This could be overcome by increasing the peg diameter such that it is greater than the hole diameter - this has the effect of confining M_A to the sympathetic direction.

Increased peg diameter (over the hole diameter) is also the solution for the situation of Figure 12.6.

Now reviewing the peg/hole-plane contacts, and the peg/hole-edge contacts that have been analysed, it is seen that this following blanket strategy will achieve invariant planes contact. The contact forces and moment is sensed at A, and -

(I) the peg is rotated about the contact point in the direction of the peg radial component of the sensed forces;

(II) when no peg radial direct force is sensed, the peg is similarly rotated <u>with</u> the sensed moment, M_A.

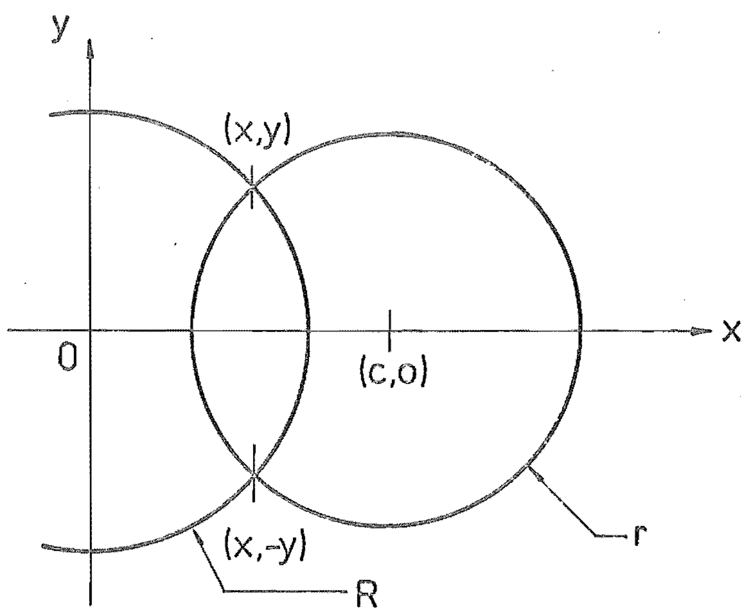
In addition, the peg diameter must be <u>larger</u> than that of the hole's (to counter the ambiguous situation in double peg edge/hole edge contacts, and to overcome the over-correction case of Figure 12.6). Another reason for an oversized peg is its necessity for the sensing of invariant planes contact.

Invariant planes contact is assumed when only a peg axial reaction is sensed at A, and therefore for this condition to be realised, the invariant planes contact attitude must engender this force configuration. If the 'over-diameter' peg is not used then :

('A') this force configuration would be misrepresented by the double peg edge/hole edge contacts situation depicted in Figure 12.2(b), and

('B') also certain invariant planes contact situations, where the peg grossly overlaps the hole, are <u>not stable</u> under a pure peg axial effort.

FIG. 12.8 PEG STABILITY ON THE HOLE PLANE



This second condition is now shown. Consider the peg of radius r, and hole of radius R in Figure 12.8.

$$\text{Equation of the hole} - x^2 + y^2 = R^2 \tag{12.4}$$

$$\text{Equation of the peg} - (x - c)^2 + y^2 = r^2 \tag{12.5}$$

Subtracting Equations (12.4) from (12.5) and rearranging yields :

$$x = \frac{R^2 + c^2 - r^2}{2c} \tag{12.6}$$

The condition for instability under a pure axial force is when the force is directed on the unsupported side of the chord of tipping, that is, when:

$$c \leqslant x \tag{12.7}$$

Substituting Equation (12.6) for x gives :

$$c \leqslant \frac{R^2 + c^2 - r^2}{2c}$$

which, upon reordering, yields :

$$c \leqslant \sqrt{R^2 - r^2} \tag{12.8}$$

Equation (12.8) implies that tipping could only occur when $R \geqslant r$. Therefore, the combination of a larger peg and a smaller hole diameters is stable in all invariant planes contact conditions under a pure axial effort.

12.3 On-Plane Hole Search

After invariant planes contact has been achieved with the help of a peg enlargement aid, that position is maintained by the peg manipulator and the peg axial effort released. Now the peg should be axially aligned with the hole, in or in near contact with the hole plane, and given the conditions outlined in the Introduction to Part Two, be within one diameter radial displacement.

The strategy for searching the hole is to test for the hole presence through measuring the peg's susceptibility to tipping when in contact

FIG.12.9 THE APPLIED TIPPING MOMENT, M_R

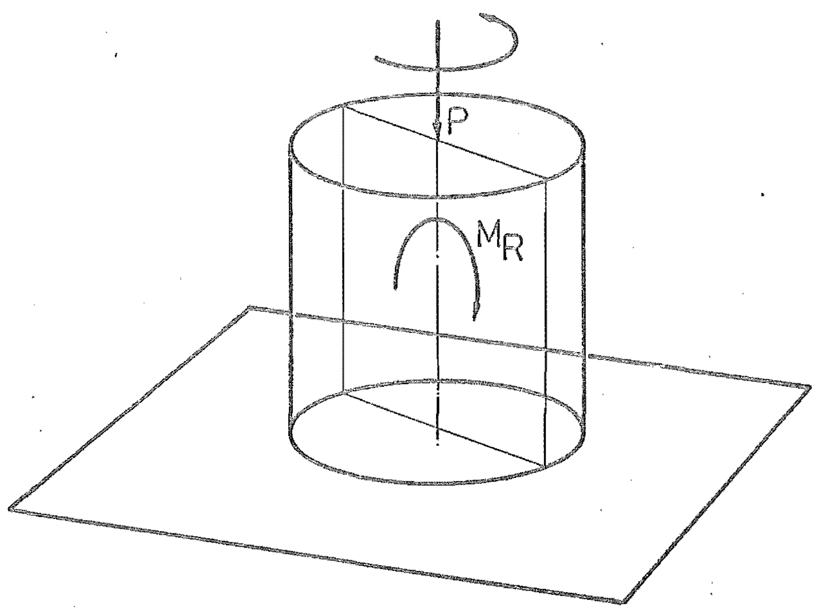
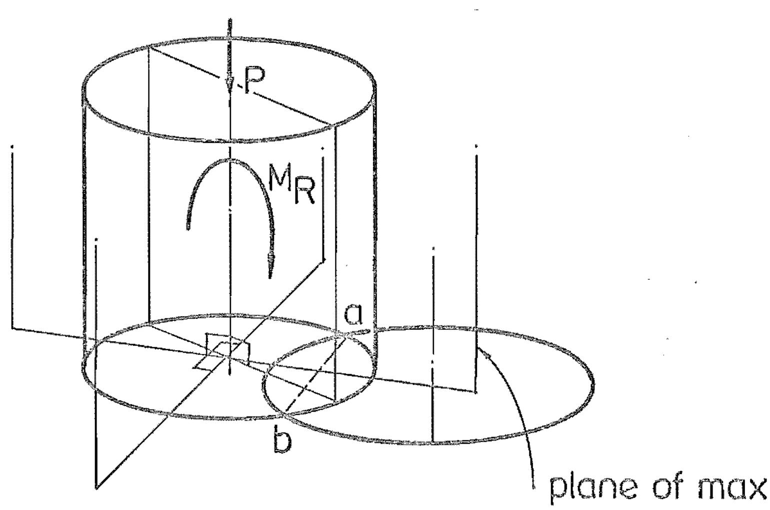
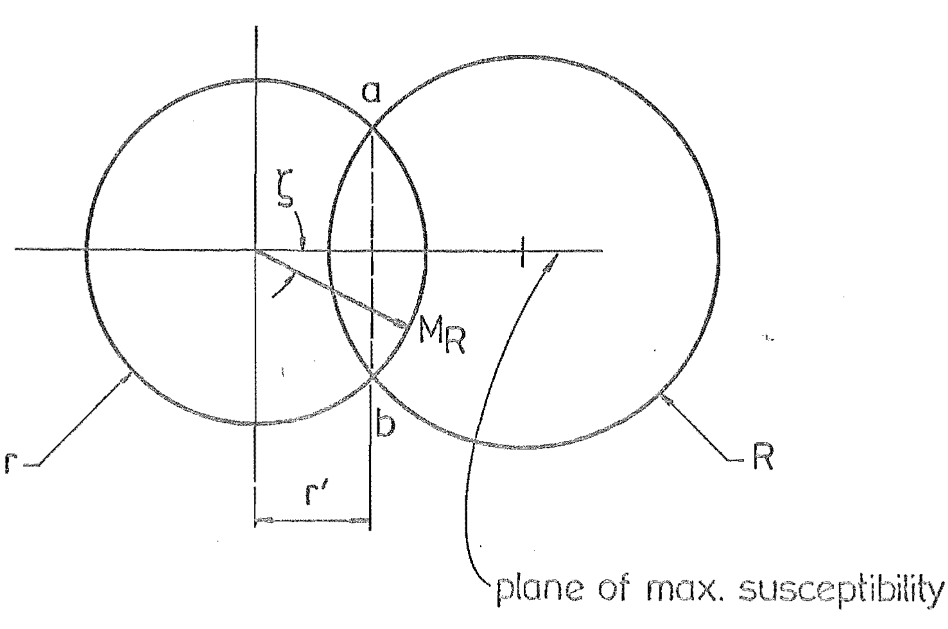


FIG.12.10 THE SUSCEPTIBILITY PLANE

(a)



(b)



with the hole plane.

The enlargement collar is retracted before searching commences, or otherwise a zone of no detection exists when the hole circle lies beneath, and within, the peg circle.

First of all, a peg axial force, P, is applied. If the radial alignment error is small (within half a hole radius, if the peg radius $\approx$ hole radius), the peg will tip in the hole direction. If no tipping occurs, then a tipping moment, M_R, calibrated such that it is just insufficient to tip the peg under fully supported conditions, is applied in a random peg radial plane, where

$$M_R \leqslant PC_x$$

The moment M_R is then rotated about the peg vertical axis. See Figure 12.9.

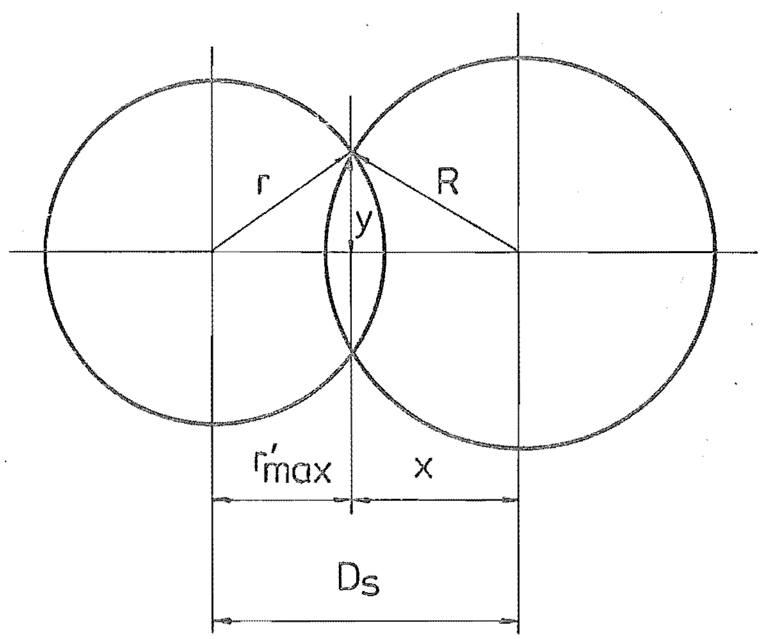
In any particular instant, M_R can be resolved into two components lying in orthogonal planes. The directions of these two planes are orientated with respect to the peg-hole overlap. The plane that is normal to the chord of tipping, ab, and containing the peg and hole axes is called the 'susceptibility plane'; see Figure 12.10. The second plane lies at right angles to this one and contains the peg axis.

When the resolved component of M_R lying in the 'susceptibility plane' is large enough to overcome the resisting moment in that direction, the peg will become unstable and tip about the chord of tipping, ab. The movement will be felt and then arrested. M_R therefore can be resolved into the two components, that lying in the susceptibility plane, M_{RS} is :

$$M_{RS} = M_R \cos \zeta \qquad (12.9)$$

If r' is the perpendicular distance from the peg axis to the tipping chord ab, then when:

FIG. 12.11 POSITION OF MAX. SENSITIVITY



$$M_{RS} = M_R \cdot \cos\zeta \geq Pr'$$

tipping will occur under the net moment ΔM_R

$$\Delta M_R = M_{RS} - Pr'$$

Theoretically, detection is possible if $\Delta M_R > 0$; in practice, however, because of damping, and the need for a reasonably fast reaction time, the maximum acceptable r' value will be significantly lower than r. The ratio of r'/r, or the sensitivity s, is expected to be :

$$s = \frac{r'}{r}, \quad s \simeq 0.6 - 0.8 \qquad (12.11)$$

Therefore, $r'_{max} = s.r.$ This will be used to find the maximum detection distance, D_s, that is, the maximum radial misalignment that a search system of sensitivity s can deal with. In Figure 12.11 the situation at r'_{max} is depicted.

$$D_s = s.r. + x \qquad (12.12)$$

But by geometry :

$$x^2 = R^2 - y^2 \quad \text{and} \quad y^2 = r^2 - (s.r.)^2$$

Therefore:

$$x = \sqrt{R^2 - r^2 + (s.r.)^2}$$

which upon substitution into Equation (12.12), gives :

$$D_s = s.r. + \sqrt{R^2 - r^2(1 - s^2)} \qquad (12.13)$$

For $R = r$, $D_s = 2.s.r.$

12.4 Planar Shift

Having now found the direction of radial misalignment, the next step is to shift the peg in that direction.

Since only the direction of the radial misalignment is found, and not its magnitude, it seems sensible to simply shift the peg under 'loose confinement' (see Chapter 10). For in this transport mode, for

FIG. 12.12 SHIFT VECTOR DIRECTION TOLERANCE

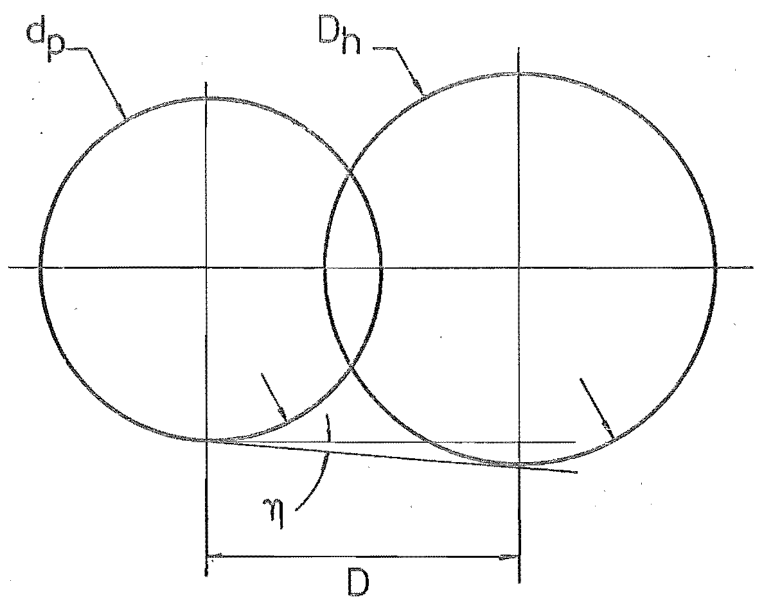
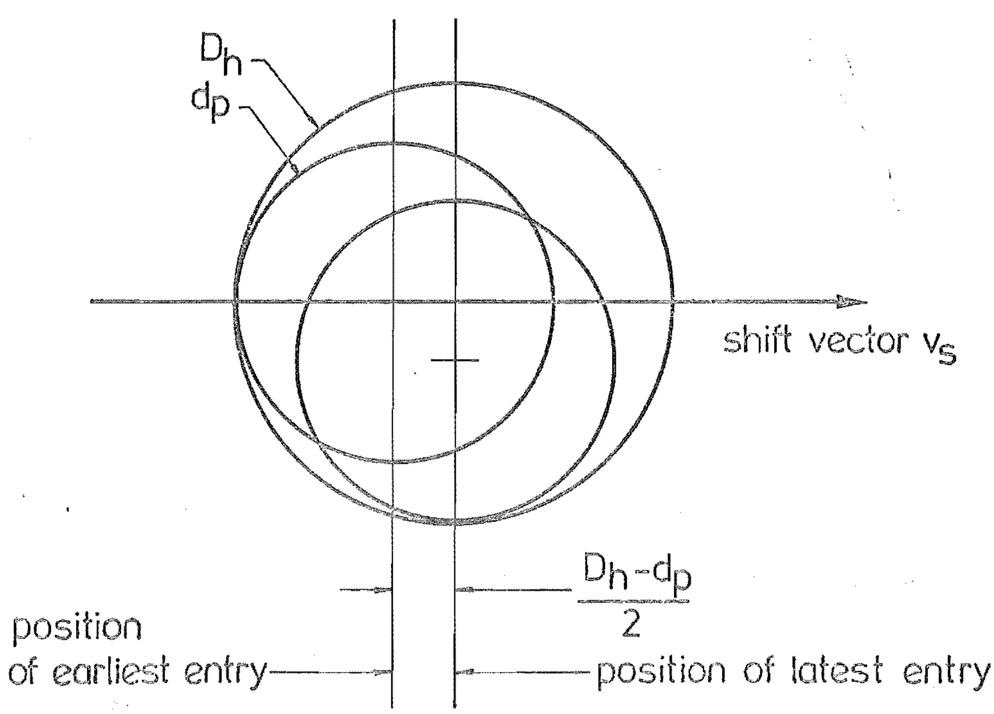


FIG. 12.13 THE EXTREMES IN PEG ENTRY POSITIONS



an unchamfered peg - unchamfered hole combination, if the peg enters into the direct entry envelope of the hole, the peg will automatically achieve complete entry. This, of course, is with the proviso that the loose confine, and the peg-hole parameters, have been matched.

For a reasonably accurate detection system, the derived shift direction should be accurate enough to achieve peg entry within the first shift. The necessary accuracy is now derived. Figure 12.12 shows a peg of diameter 2r, and a hole of diameter 2R, radially misaligned by a distance D. Assuming that during the shift the peg's movement vector is identical to that of the confine - which is a good assumption as this is what happens when the peg is travelling in its maximum stability position within a cylindrical confine - then the maximum angular deviation for the shift is given by η,

$$\eta = \tan^{-1} \frac{(2R - 2r)}{2D} \qquad (12.14)$$

When the peg enters into the direct entry envelope of the hole, and begins to descend into the hole, jamming of the peg in mid-entry, between the hole and the confine may occur. This can be prevented by :

(1) stopping the confine movement before jamming occurs; that is, as soon as entry commencement is detected; or

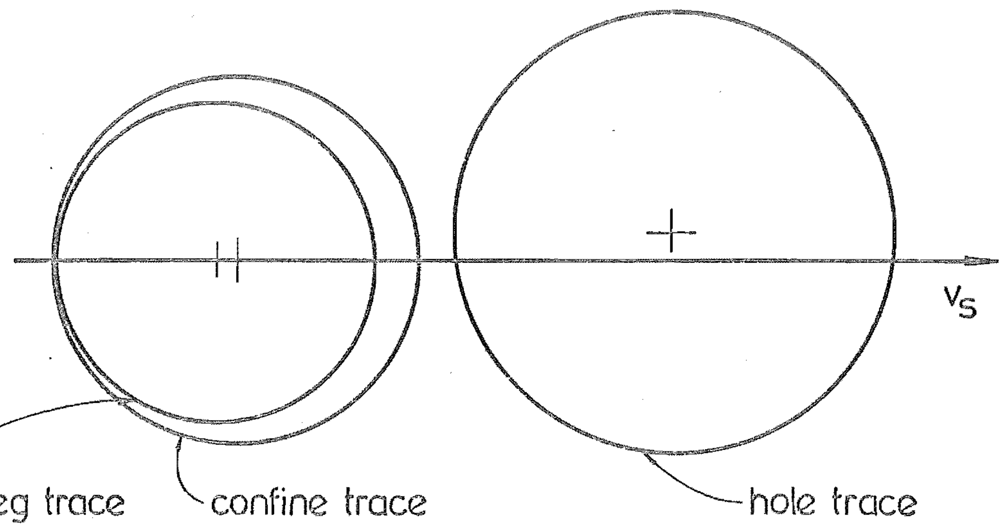
(2) regulating the shift velocity such that entry is completed before jamming could arise.

These conditions, (1) and (2), are meaningless without an indication of the time, or the distance, that is allowed for each action; this is to be determined now.

Figure 12.13 shows the two extreme positions of the peg with the hole entry envelope at which entry will begin. If the shift vector passes through the hole axis, then the peg will commence entry at the 'early' position (distance $\frac{D_h - d_p}{2}$ before the hole axis position).

FIG. 12.14 THE LATEST ENTRY POSITION

(a)



(b)

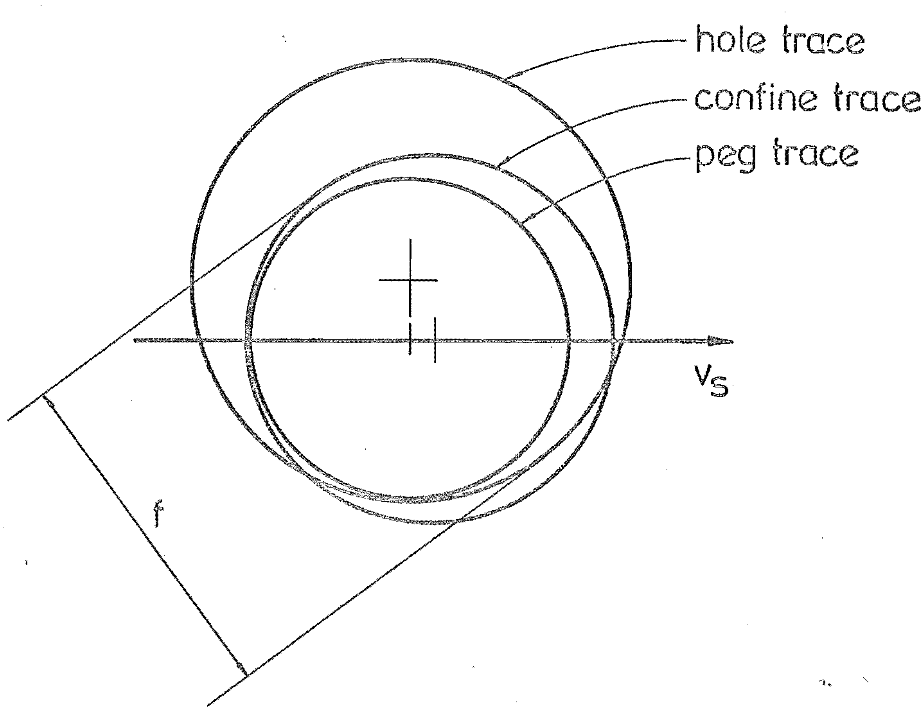
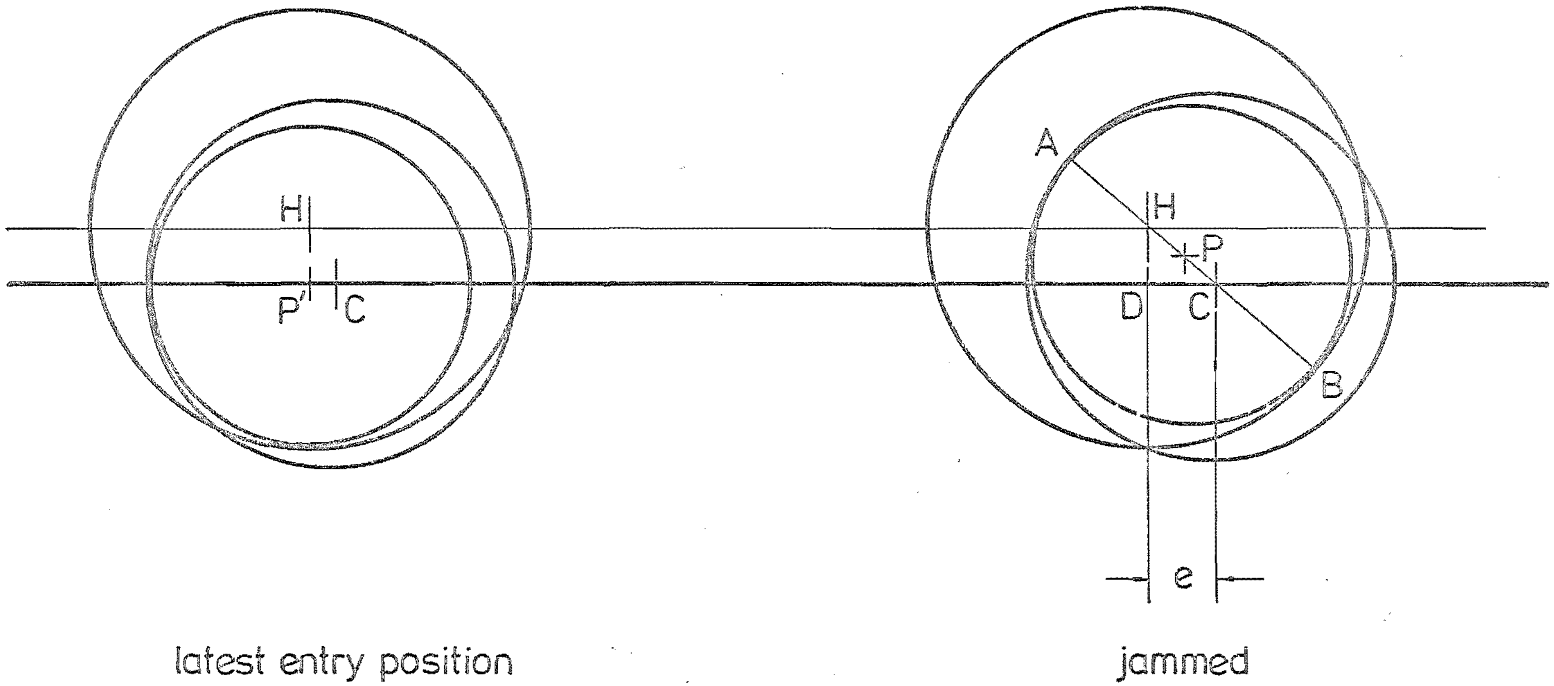


FIG. 12.14 (c) Peg jammed between hole and confine



If the shift vector does not pass through the hole axis, but peg entry is still achieved, then the latest entry commencement position is where the peg and hole axes are laterally level. It is this latest entry position that gives :

(a) the minimum time for stopping the holder once entry commencement is detected;

(b) the lowest shift velocity, if shift velocity is to be regulated so that it is slow enough to allow complete entry of the peg under all conditions without jamming.

This 'latest' entry position will therefore be further investigated. Figure 12.14(a) shows a peg being shifted within a loose confine towards the hole; Figure 12.14(b) shows a situation in the latest entry commencement position. Consideration of the situation in Figure 12.14(b) will clearly show that the continuation of the confine movement after entry commencement will roll the peg around the hole as it is still entering, and if either the confine has not stopped shifting, or the peg has not completed entry, before the maximum distance between the confine and the hole walls, f, falls below the peg diameter, d_p, jamming will result.

The distance of shift, e, beyond the entry commencement point before this happens, is a function of d_p, D_h, and D_c. D_c is the confine diameter. To determine e, consider Figure 12.14(c) which shows the peg in the jammed position. Here the points A, B and P are co-linear; therefore the confine and hole centres, C and H respectively, must also lie on the same straight line. The distance sought, e, is expressed in Figure 12.14(c) as DC.

By geometry :

$$HC^2 = HD^2 + DC^2$$

and $$DC^2 = e^2 = HC^2 - HD^2 \qquad (12.15)$$

Now for HD : see Figure 12.14(c) latest entry position diagram,

$$HD = HP' = \frac{D_h - d_p}{2} \tag{12.16}$$

and for HC:

$$HC = HP + PC$$

and $HP = HB - PB$

i.e. $HP = D_h - d_p$

and $PC = AC - AP$

i.e. $PC = D_c - d_p$

$\therefore$ $HC = D_h - d_p + D_c - d_p$

i.e. $$= D_h + D_c - 2d_p \tag{12.17}$$

Thus, substituting Equations (12.16) and (12.17) into (12.15) yields :

$$e^2 = HC^2 - HD^2$$

$$e = (D_h + D_c - 2d_p)^2 - \left(\frac{D_h - d_p}{2}\right)^2$$

$$e = \sqrt{(D_h + D_c - 2d_p)^2 - \left(\frac{D_h - d_p}{2}\right)^2} \tag{12.18}$$

Therefore, e is very small, about the size of the radial clearance between the peg and the hole, i.e. in the order of 0.02 - 0.2mm.

So it seems that the methods of preventing jamming outlined before will not work due to the smallness of the quantity e. That is to say, it is very difficult to detect the peg entry commencement and stop the manipulator shift within, say, a distance of 0.025mm. Similarly, to slow the overall peg shift velocity down to that for which a peg of say 5cm length can have sufficient time to complete entry before the manipulator confine has shifted 0.025mm is equally untenable. A 5cm long peg takes about .1 second to complete entry under gravity.

Therefore some alternative solutions are necessary.

In addition to terminating the shift as soon as the peg entry commencement is detected, the holder of the confine could be radially spring loaded such that the manipulator overshoot will be taken up by the springs. This will, however, apply a side load to the entering peg. This seems to be the way a blind-folded human assembler tackles the problem.

Another solution entails further sensing. The closeness of the hole is detectable through the increased contact normal force on the side of the manipulator confine (see Figure 10.11, and section 10.2). This feature could be used to indicate an imminent entry, and thus enable the shift velocity to be suitably reduced. A reasonable approach velocity coupled with a very slow final phase is acceptable. For this strategy, for a 5cm long peg and $e = .025$mm, the maximum final shift velocity is ~ 0.25 m.m/sec.

Finally, there is the question of the arbitary shift distance. A consideration of the problem will show that the shift distance, D_d, can vary within

$$0 < D_d \leqslant D_s \tag{12.19}$$

and still maintain the system's detection ability (if the shift direction error is small). Another factor is the accuracy of the shift direction, because if the chances of entry are reduced by inaccuracies, it is better to derive a new shift direction. Equation (12.14) relates the required angular accuracy to the given peg-hole clearance and the shift distance D_d. That is :

$$\tan \eta = \frac{D_h - d_p}{2D_d} \tag{12.14}$$

Rearrangement gives :

$$D_d = \frac{D_h - d_p}{2(\tan\eta)} \tag{12.20}$$

which gives D_d in terms of the peg-hole clearance and the accuracy ($\pm\eta$) of the final shift direction vector.

Therefore, the magnitude of D_d is bound by either Equation (12.19) or (12.20) whichever gives the smaller.

This then is the conceptual description and analysis for a foreseen solution to the placement problem, which in terms of hardware sophistication, falls into the desired cost category of solution systems. This proposed system could give to flexible handling devices the necessary additional ability to enable their application as an inexpensive tool for flexible automation. Supervisory control and the logic elements for this solution are simple enough to be hardwired, or if coupled to a computer, will require a very low computation time.

CHAPTER THIRTEEN

EXPERIMENTATION

13.1 Introduction

The next step following the conceptual analysis of the solution system is the experimental verification of the main ideas.

The three principal components of the system are :

(1) Invariant planes contact through simple tactile feedback;

(2) On-plane hole search through the measurement of the direction of tipping susceptibility;

(3) Planar shift to entry which again involves tactile sensing.

Parts (1) and (3) involving tactile sensing, and delicate manoeuvres in the manipulator wrist and fingers, is essentially a problem in robot hand design and control. Part (2), on the other hand, pertains more to the particular solution system being examined and is the central concept in the 'invariant planes contact' solution.

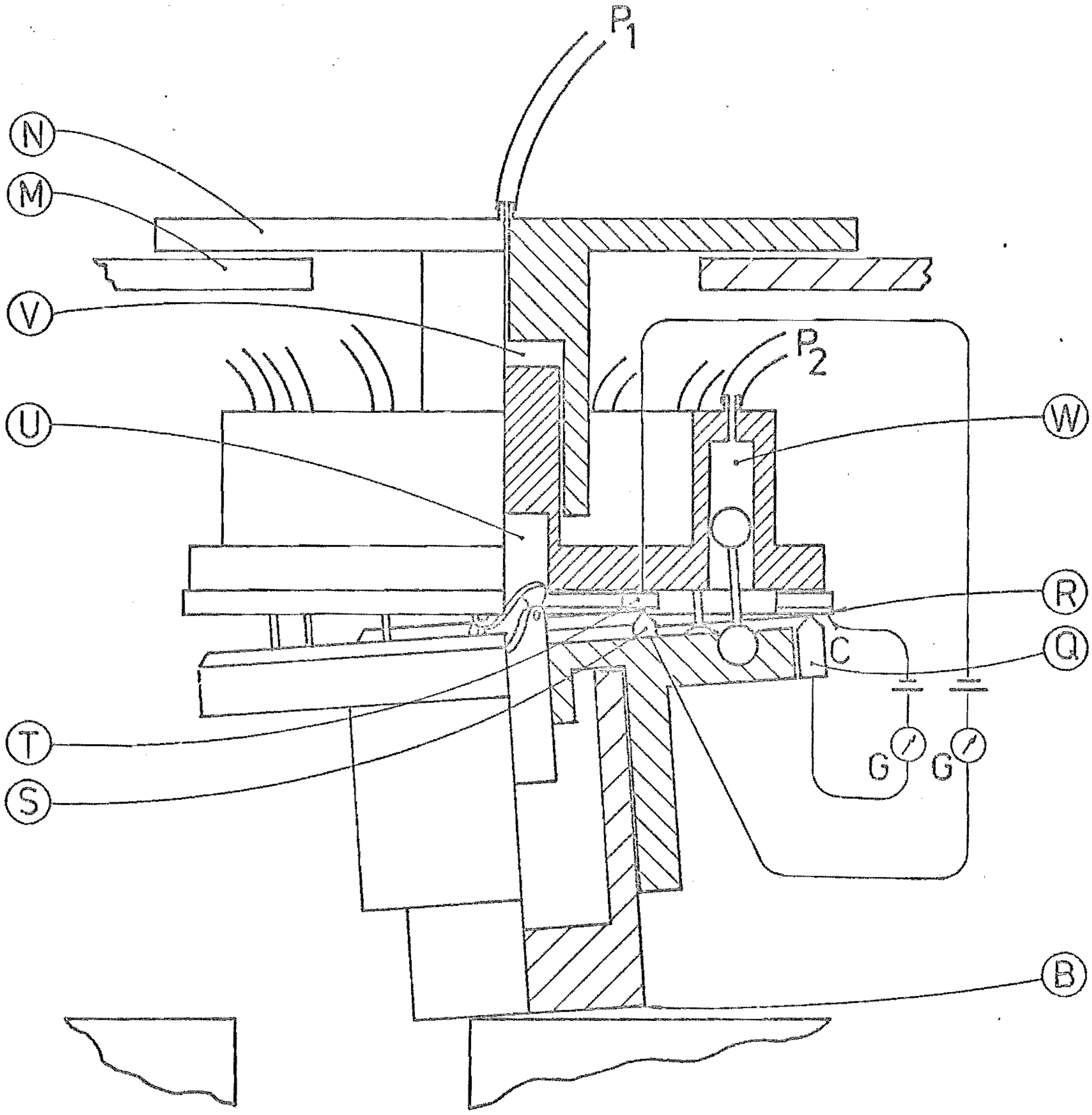
The problems of tactile sensing through a robotic hand are varied and many, and form a part of the robotic arm/manipulator problem as a whole. At present in parallel development with this project are research programmes aimed at :

(a) producing a sufficiently sophisticated general purpose research robot arm/hand that can be used to test such assembly concepts and strategies as this one;

(b) developing a mini-computer based control system to operate this robot in the required manner.

The ultimate aim in this venture is a piece of robotic hardware that can be used as a test bed for all the various assembly method proposals that will arise from the research into the multiple aspects of automatic assembly.

FIG.13.1 PEG TIPPING HEAD



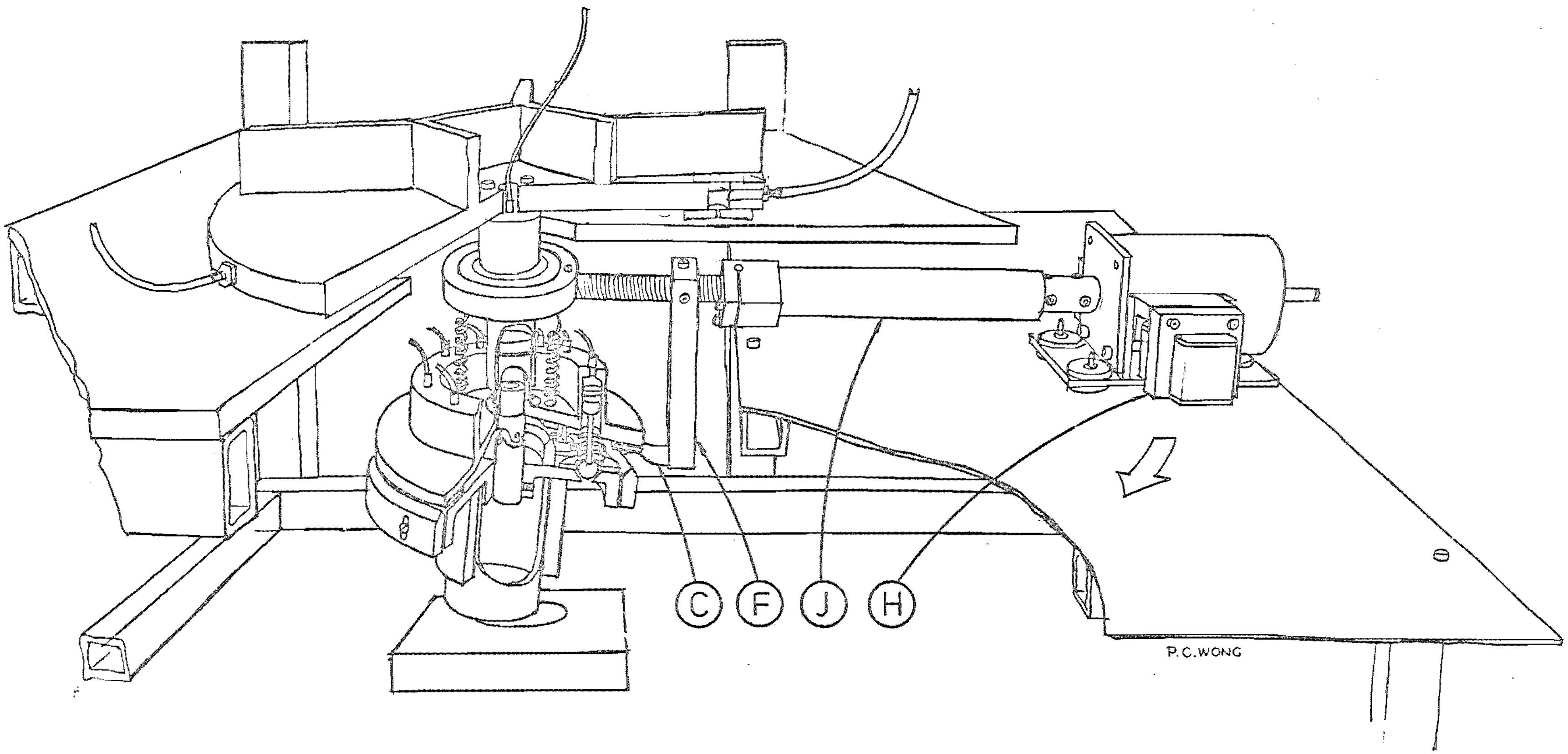


FIG.13.2 SKETCH OF TEST RIG

Thus, the experimentation here shall be confined to testing the adopted strategy of on-plane search. A simple experiment will therefore be devised to test this concept, and from this it is hoped that relevant performance parameters could be deduced. For this test rig the emphasis is on simplicity and expediency - the sole aim is for verification of the concept.

13.2 Implementation of the Idea

The concept to be verified is described in Section 12.3. Briefly, the peg is in its invariant planes contact position, in overlap with the hole. When the resolved component of the applied tipping moment in the peg-hole overlap direction is sufficiently great, instability will result (due to a decrease in geometric support in that direction). This movement is detected, and its direction registered - this corresponds directly to the direction of the peg-hole radial misalignment.

The final design for the test apparatus is shown in Figure 13.1 and 13.2.

The tipping moment application, and the resulting roll of the peg, is achieved through the use of a swash mechanism centred on the universal joint, U. To allow for the manifested vertical and horizontal adjustments caused by the finite roll of the peg, the swash head is mounted through the vertical piston, V, and the frictionless horizontal table, M, respectively.

Now for the functional description:

Tipping of the peg is sensed through the flex or deflection of the holder due to the manifested bending moment. Whereas in a computer driven robot design the sensing of the direction of tip can be performed with no moving parts involved (like using strain gauges to sense flex), in this test rig, the most expedient method is to utilise a finite rotation (about U) against stops (the rings R and Q). The occurrence of a tip is sensed by the contact of the rings T and S which completes an electric circuit. Once a tip is registered, further search procedures are stopped and the direction of that tip is determined. Direction sensing is through the use of the rings R and Q which contact upon tipping. The upper ring, R, is an annulus of thin radial strips, each alternate strip being a conductor or an insulator. The lower ring Q is electrically alive. So, when R touches Q one of the conductor strips on R (the contacted one) becomes alive. By sweeping the probe C around R, this live segment is located by the completion of an electric circuit. The radial line that this segment lies on, is the direction of tipping; that is, the direction of the hole and subsequently the direction of the planar shift.

Operationally, the first step is the pressurization of the air cylinder V. This brings the peg into hole contact. If the overlap is sufficient for the peg to become unstable under this pure axial effort, the peg will tip. This will be indicated by the rings T and S, and the direction of the tip is found through the rings R and Q. The hole search is then terminated.

If tipping is not indicated after the activation of the cylinder V, the rotation of the calibrated tipping moment is initiated. This is performed by the additional activation of the ring of air cylinders, W, in cyclic succession. The ratio of the air pressures in each, $P_1 : P_2$, is calibrated such that when the peg is in pure hole plane contact, P_2 is just insufficient to tip the peg about its edge (a point such as B). During the cyclic activation of the air cylinders W, if the contact rings T and S register a tip, the multiplexing is halted, fixing the tipped mode. The direction of the tip (the hole) is then found.

In order to demonstrate the operation of the direction sensor, and to test its accuracy, the manipulator head is designed so that it can be driven laterally (on air bearings) on the table M. The manipulator head is connected to a screw jack J (driven by a stepper motor) for the planar shift (see Figure 13.2). The direction sensing sweep probe C is attached to the screw jack via a strut F. In this way the probe C is swept by swinging the screw jack, automatically lining the jack in the detected direction of the hole (and shift).

Operation of the entire system is in the following manner. Refer to Figures 13.1 and 13.2.

(1) The air bearings on the manipulator head support (N) and the stepper motor support are pressurized so the whole head is 'floating'.

(2) Cylinder V is pressurized. Peg-hole contact occurs.

(3) If tipping is sensed by the rings T and S (shown by electric circuit completion), go to step 5; if not, go to step 4.

(4) Pressurize a cylinder W and multiplex around in cyclic order until tipping occurs (sensed by T and S) and then halt the cylinder multiplex.

(5) De-pressurize the manipulator head support air bearings - this serves to lock the manipulator head in its last position.

(6) Sweep the ring R, using the probe C, by swinging the screw jack around the manipulator head (while the stepper motor and screw jack are supported on its air bearings). Note: due to the physical limitations of this rig design, the sweep angle is limited to a quadrant of about 110°, and therefore the peg and hole will have to be set up to tip in the corresponding sector.

FIG.13.3 TIPPING FORCES

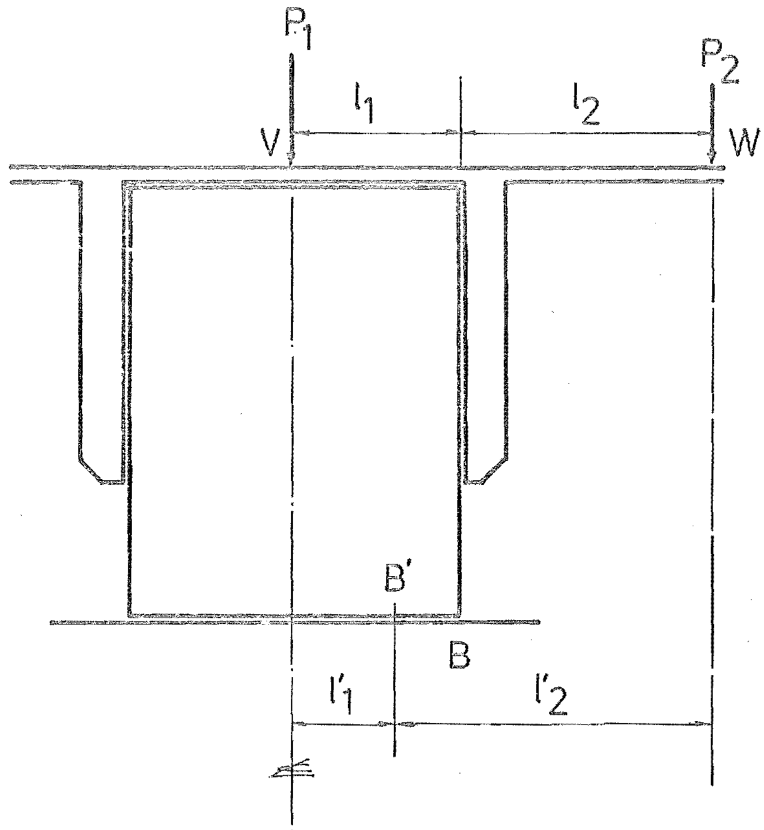


TABLE 13.1 TEST DATA

P_1	P_2	P_1/P_2	D_s
N/m^2 (psi)	N/m^2 (psi)		m (inch)
$\pm 1 \times 10^4$	$\pm 1 \times 10^4$		± 0.0005
4.14×10^5 (60)	3.79×10^5 (55)	1.09	0.0239 (0.94)
3.45 " (50)	3.24 " (47)	1.06	0.0226 (0.89)
3.10 " (45)	3.03 " (44)	1.02	0.0203 (0.80)

(7) Once the direction of tip is located by C , the screw jack direction is held by de-activating the screw jack motor carrying air bearings, and activating the holding magnets, H.

(8) For the planar shift the manipulator head support air bearings are re-pressurized.

(9) The stepper motor is started to drive the manipulator head (and peg) towards the detected hole.

13.3 Test Jig Design

The test jig was designed to operate in the manner described in Section 13.2. A photograph of the jig appears in Figure 13.4.

Although on the whole the operational concept and consequent design is simple, in this section some salient design points are discussed.

The first point that is of interest is the relative disposition of the pistons V and W. Figure 13.3 shows diagrammatically the arrangement of the forcing geometry. The lines of action of the central piston V (pressure P_1) and the peripheral pistons W (pressure P_2), are shown in relation to the geometry of the manipulator head and peg. Let the areas of the pistons V and W be A_v and A_w respectively. In the calibration of the pressures, P_1 and P_2, the final ratio arrived at is governed by the moment relation :

$$P_1 A_v \ell_1 = P_2 A_w \ell_2 \qquad (13.1)$$

$$\text{i.e.} \quad \frac{P_1}{P_2} = \frac{A_w \ell_2}{A_v \ell_1}$$

which gives a moment balance about the contacting peg edge B. In practice, the operation ratio P_1/P_2 would be slightly higher than that due to Equation (13.1) in order to give stability to the peg in directions of no peg-hole overlap.

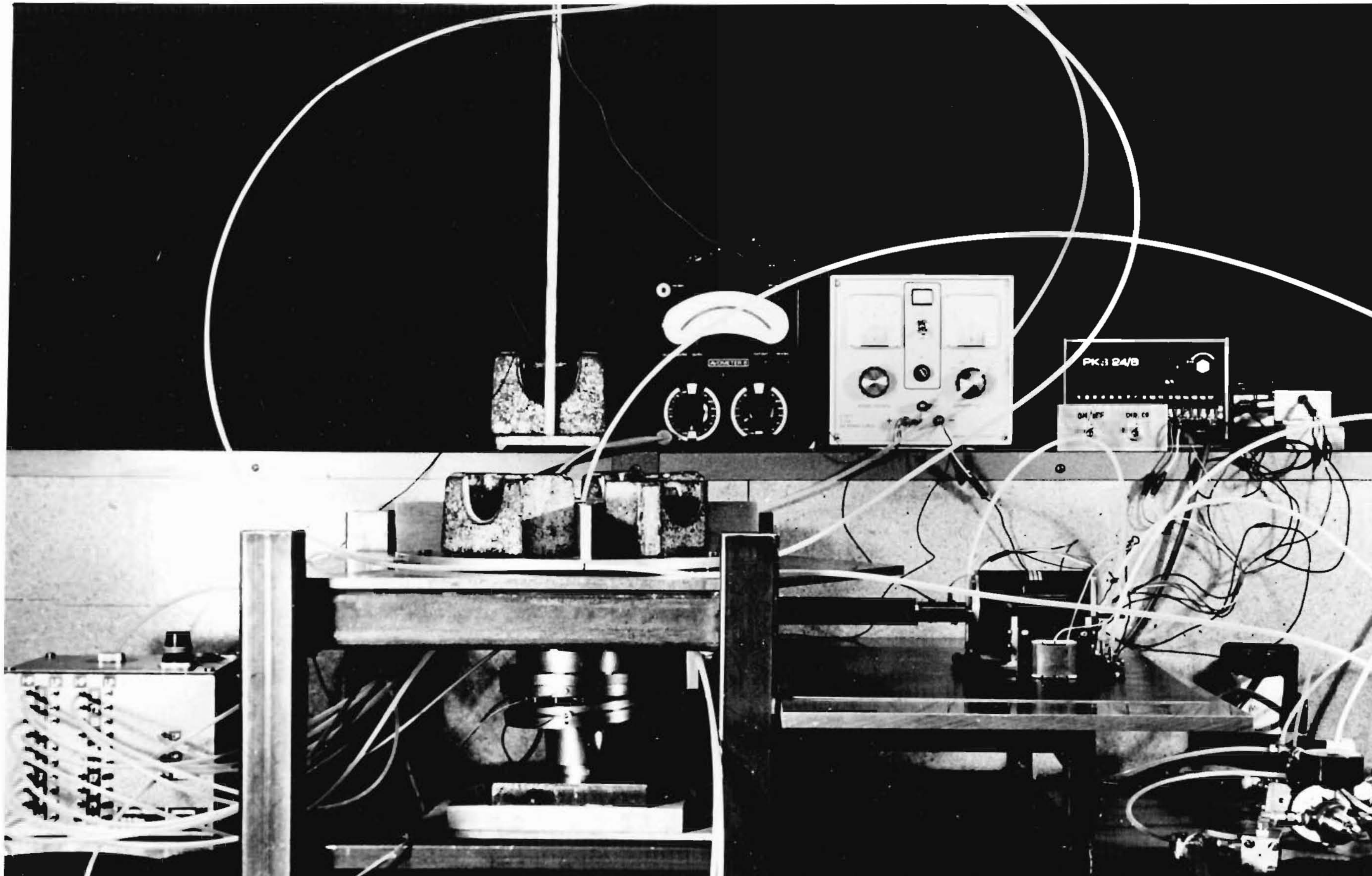


FIG. 13.4 PHOTOGRAPH OF TEST RIG

When peg-hole overlap occurs and the position of the support point shifts back to B', the developed tipping moment, ΔM_R, becomes :

$$\Delta M_R = P_2 A_w \ell_2' - P_1 A_v \ell_1' \qquad (13.2)$$

This expresses ΔM_R as a function of P_1, P_2, ℓ_1' and ℓ_2'. Now ℓ_1' and ℓ_2' depend on the overlap geometry, the quantities P_1 and P_2, however, though related by Equation (13.1) can be varied to change the magnitude of ΔM_R. A large ΔM_R for a given ℓ_1', ℓ_2', implies a better systems sensitivity s (Section 12.3)

The next area needing further comment, is the direction-of-tip sensor. The ring, R, consisting of alternate radial strips of conductor and insulator, was formed by printed circuit methods. Each radial segment is 1° wide.

Finally, as a test of the accuracy of this form of tip direction sensing, a screw jack (and stepper motor) was incorporated into the design to perform the planar shifting. The sweep probe C is attached to the screw jack (see Figure 13.2), so the screw jack direction placement is performed simultaneously with the tip direction location. The sensed direction is deemed accurate if the shift leads the peg through the direct entry envelope of the hole. This, of course, can be shown best by the peg entering the hole. The problems of planar shifting will be recalled from Section 12.4; so, because of the lack of a hole proximity indicator to enable a variable velocity shift to be used, a constant shift velocity, V_{sc}, will have to be used. V_{sc} must be sufficiently slow to enable the peg to drop clear of the manipulator before jamming the peg, between the manipulator and the hole, could occur. The minimum distance travelled before jamming, e, (Section 12.4) is expressed as :

$$e = \sqrt{(D_h + D_c - 2d_p)^2 - \left(\frac{D_h - d_p}{2}\right)^2} \qquad (13.3)$$

The time, t, for a particle to descend a distance y under gravity, g, is given by :

$$t = \sqrt{\frac{2.y}{g}} \qquad (13.4)$$

Combining Equations (13.3 and (13.4) gives the maximum V_{sc} :

$$V_{sc} = \frac{e}{t} = \frac{\sqrt{(D_h + D_c - 2d_p)^2 - \left(\frac{D_h - d_p}{2}\right)^2}}{\sqrt{\frac{2y}{g}}} \tag{13.5}$$

This assumes an assembly acceleration of gravity, which due to contact and damping forces, may not be true, so in practice the assembly acceleration is reduced to K.g where :

$$0 < K \leqslant 1$$

Therefore :

$$V_{sc} = \sqrt{\frac{(D_h + D_c - 2d_p)^2 - \left(\frac{D_h - D_p}{2}\right)^2}{\frac{2.y}{Kg}}} \tag{13.6}$$

For the actual test jig the peg parameters are :

peg diameter, P_d = 50.8mm (2.000")

clearance drop, y = 50.8mm (2.000")

(a) for a hole diameter, D_h = 53.34mm (2.100")

for a confine diameter, D_c = 53.34mm (2.100")

for a coefficient K = 1.0

V_{sc} = 48.36mm/sec (1.904 inch/sec)

(b) for a hole diameter, D_h = 53.34mm (2.100")

for a confine diameter, D_c = 53.34mm (2.100")

for a coefficient K = .5

V_{sc} = 34.18mm/sec (1.346 inch/sec)

(c) for a hole diameter, D_h = 51.04mm (2.010")

for a confine diameter, D_c = 53.34mm (2.100")

for a coefficient K = .5

V_{sc} = 19.41mm/sec (0.764 inch/sec)

(d) for a hole diameter, D_h = 50.85mm (2.002")

for a confine diameter, D_c = 53.34mm (2.100")

for a coefficient K = .5

V_{sc} = 18.01mm/sec (0.709 inch/sec)

(e) for a hole diamter, D_h = 50.85mm (2.002")

for a confine diameter, D_c = 52.07mm (2.050")

for a coefficient K = .5

V_{sc} = 9.17mm/sec (0.301 inch/sec)

13.4 Test Results

The test rig was operated in the manner described in the sequence of operation (Section 13.2).

Details of the specific peg, hole and confine sizes used are :

peg dia., d_p = 50.29mm (1.98 in)

hole dia., D_h = 51.31mm (2.02 in)

confine dia., D_c = 50.80mm (2.00 in).

Both the peg and the hole were unchamfered.

The first run of tests were on the calibration of the pressures in the central and peripheral air cylinders, P_1 and P_2 respectively. As predicted, the detection sensitivity, s, improved with the increase of the pressure ratio P_1/P_2 (Section 13.3). Over a limited range of available operating pressures the calibrated ratios (P_1/P_2), and the corresponding maximum detection distance, D_s, as measured, are tabulated in Table 13.1. Thus, with this sensing head, over the range of pressures used, D_s is approximately one peg radius in magnitude. The corresponding system sensitivity, s, is about 0.45.

The use of the radially segmented ring R, and the tilting contact ring Q (at a maximum swash angle of 5°), proved adequate in directional accuracy for the sensitivity of the detection head. In operation, when contact between the rings R and Q occurred, four conducting segments were contacted; this implied the additional step of finding the central radial segment through which lay the bisector of the sector in contact. For a contact sector of four conductors width, the central segment is a non-conducting one of 1° width. Therefore, with this directional accuracy of 1°, the maximum acceptable shift distance, D_d, can be calculated in accordance with Equation (12.20):

$$D_d = \frac{D_h - d_p}{2 \tan(\eta)}$$

$\eta = 1^{\circ}$, $D_h = 51.31$mm, $d_p = 50.29$mm. This gives a D_d value of 35.89mm, which is in excess of the maximum detection distance, D_s'. In practice, this adequacy was verified by the successful performance of this phase of the experiment.

The shift velocity, V_{sc}, used, was below that of the maximum allowable according to Equation (13.6). V_{sc}, calculated for the specific peg, hole and confine dimensions, and using a factor $K = 0.9$, was 13.38mm/sec (0.527 inch/sec).

The experiment was carried out with the controls of the switching sequence remote from the test rig, such that the element of human intelligence was absent during the test.

Operation of the misalignment direction detection, planar shift, and peg insertion, was consistently successful.

CONCLUSION TO PART THREE

In this section the concepts and data derived in Part Two were used in an attempt to derive a solution to the entire problem of placement. Useful strategies and methods of alignment derived in Part Two evolved out of the examination of contact between the peg and the hole. Each method of alignment, however, does not extend outside one type of contact form (peg edge/hole plane, peg edge/hole edge, etc.); therefore, as a complete solution to the problem of placement (which involves all the contact forms), these methods are too narrow. So in Part Three, complete solutions, using the information derived in the previous work, were sought.

A list of solutions was then briefly reviewed. Here, the adaptability to parameter changes, the number of extraneous elements (other than the peg and the hole) involved, computational complexity, and the demands made on initial alignment accuracy, varied from solution to solution. The common factors, however, are :

(1) All the solutions are based on the concepts developed in Part Two, enveloping one or more of these ideas.

(2) All the solutions (with the exception of the 'Multiple Contact one) are regarded as 'mid-range' solutions.

Obviously, within this list some solutions would be more specific to the cylindrical peg-hole problem, while others demonstrate a principle or a technique that may eventually have a wider application. What is regarded as important, is not a solution that can be applied now to peg-hole assembly, but one for which the peg-hole problem is but a first application of a principle. Therefore, by this criterion, the system of solution named "Invariant Planes Contact" was selected for further development.

The various phases of this invariant planes contact solution were then discussed. The analysis is both qualitative and quantitative. The first phase of this solution is to achieve an invariant relative orientation between the two components (peg and hole); this is done by using simple tactile feedback, and the singular contact form is peg edge/hole plane. The presence of the hole is 'removed' by making the peg diameter greater than that of the hole by means of an auxiliary collar around the peg. The second phase determines the direction of misalignment; this is done by sensing the direction of peg-hole overlap through measuring the change in peg stability in that direction. Specifically this direction is least able to resist a tipping moment lying in the aligned peg radial plane. The third phase of the solution shifts the peg into the hole; since the magnitude of the radial misalignment is not found, this is achieved by a planar shift under loose confinement.

Finally, the central concept of this solution was tested in hardware. Phase two, the sensing of the direction of misalignment by measuring the direction of susceptibility to tipping of the peg was implemented as a mechanism. Subsequent testing showed the principle to be practicable, and performance data were measured for this particular method of implementation.

CHAPTER FOURTEEN

SUMMARY OF CONCLUSIONS

The work appearing in each of the three main parts of this thesis has already been discussed in their respective concluding sections. Here, in the final conclusion, these sections will be briefly reiterated, so that the work in this project can be reviewed and discussed as a whole.

Since this is the first Ph.D. thesis to appear on this topic from the University of Canterbury, it was felt valuable to discuss the initiating factors for this line of research, and subsequently, the resulting stance adopted on the type of solution that was deemed relevant for the prevailing conditions. A brief look at industrial history, and a review of the present status of industrial automation and recent ventures into flexible automation was followed by a discussion of the conditions that made the present favourable for an investigation of this nature: labour dissatisfaction, rising labour costs, and the arrival of the mini-computer. These factors, when married to the needs of New Zealand's industry, gave rise - in this interpretation - to a quest for a method of flexible automation of <u>mid-range</u> complexity and cost.

Thus, this preamble sets the direction that this project will take. At this level of research, however, the findings, and indeed the resulting methods, are applicable to any assembly strategy or solution. It is mainly in the manner and extent that these methods feature in the final system of solution that the overall policy has influence.

Accordingly, the work fell into three major parts. The first part, Part One, was initially concerned with the location and definition of the problem, and latterly to expand that on more rigorous terms. The investigation was confined to the assembly of a cylindrical peg into a cylindrical hole. The peg-hole combination was considered to be one of the fundamental forms for which analysis would provide grounding for eventual higher assembly combinations. Part Two is more concerned with the method of solution; it was felt that simple tactile feedback might provide the key to the mid-range solution that was sought, so the work here establishes the fundamentals of body contacts and reaction forces. The possibility of using these in simple tactile feedback, and associated tactile methods of solution, was investigated. The final section, Part Three, is concerned with methods of solution. The findings of Part Two were used singly, or together, as bases for solution proposals. The conclusions and findings of these three parts will now be discussed more fully.

In Part One the broad conclusions can be briefly summed up as :

(1) The various parts of the assembly operation were examined in terms of demands on the operator (operator constraints). The fitting, or placement, stage was found to be intrinsically the most difficult due to the functional requirements of the design of the assembly components themselves.

(2) The placement stage, thus isolated as the problem area, was further divided into Phase I - searching, and Phase II - assembly. If Phase I is regarded as a 'search and align' stage, then how closely must it align for Phase II to be successful? In other words, what are the output conditions for Phase I?

(3) Consideration of clearance and alignment showed the success of Phase II to be dependent on -

(a) the intelligence of the operator; and

(b) the properties of the assembly - clearance, frictional coefficient, geometry, mode of handling, etc.

So these factors set the output conditions of Phase I.

(4) For a low intelligence, direct placement type of Phase II operator, the operator constraint is isolated to one of physical alignment alone. For this case: the radial misalignment of the peg on delivery must be contained within a tolerance envelope which is related to the peg-hole clearance, the angular misalignment envelope is determined through the jamming criterion.

(5) The next topic was the nature of an operator. An activity can be machine performed within a range of two extreme manners : one in which it is performed by a general purposed, high "consciousness" robot, and the other where it is carried out by an inflexible, specifically designed, low "consciousness" mechanism. A mid-range solution is seen to lie midway in this continuum.

In Part Two the phenomenon of body contact was examined to provide greater insight into the mechanics of assembly; at the same time, from this study a mid-range strategy for Phase I was sought. The broad conclusions can be summed up as follows :

(a) When a peg-hole contact occurs, a reaction force results at the contact point, and this reaction force is dependent on several factors - the forcing effort, the peg-hole axes alignment angle, the contact friction, and the contact geometry. In a peg-hole situation, there exists three available forms of contact - line/line, line/plane, and plane/plane. For the contact forms associated with peg-hole axial misalignment - line/line and line/plane - there is, in general, no direct relationship between the sensed reaction and the gross peg-hole misalignment.

(b) If no relationship exists between the sensed reaction and the gross peg-hole misalignment, then perhaps a strategy could be based on correction in the <u>directions</u> of the sensed forces and moment. The application of this idea to the various forms of contact showed that within certain alignment bounds, for some contact forms, this concept held (for example, line/line, line/hole-plane). Thus, for some contact forms a simple tactile feedback alignment strategy is derivable; however, each contact form needed a specific strategy which is not applicable to the entire range of contact forms likely to be encountered. A workable solution must somehow amalgamate these individual strategies and be applicable to every contact form that is encountered.

(c) Next to be examined in further detail because of their anticipated usefulness were two other associated aspects of body contact. The first, chamfers, was analysed in principle so that its performance could be optimised. The concept of directional friction coefficient 'chamfers' was also investigated. The chamfer is a useful alignment mechanism provided that chamfer contact can be guaranteed. The second area examined was the loose confinement manipulation of a peg in hole-plane contact. This aspect is important in the transportation of the peg, which is necessary to eliminate misalignment. Here, relationships were derived relating peg contact forces and parameters like friction coefficients, peg geometry, transport velocity, etc., such that the mechanics of this transport mode was understood.

The study of Part Two contributed to a better understanding of the activity at the assembly interface and at the same time, offered some ideas for the detection and correction of misalignments.

In Part Three the engineering aspect of application is the main concern: the information and some methods derived in Parts One and Two were used as the basis of solution proposals, all of which are related by the common theme of tactile sensing. The work of Part Three can be summarised as follows :

(i) Various systems of solution were proposed. All these involved simple tactile sensing to some extent and (with one exception) are regarded as mid-range types of solution.

(ii) A particular proposal - Invariant Planes Contact - was selected for further development on the recommendations of generality and potential for wider application. This system of solution divides placement Phase I into three distinct stages, thus overriding the difficulty of finding one solution to all the diverse forms of contact found in one peg-hole assembly. These stages are :-

(a) Contact of two invariantly oriented planes (through simple tactile feedback) to reduce the general misalignment to a planar problem.

(b) Sensing the peg-hole overlap direction (direction of radial misalignment) by measuring the direction of minimum peg support (using tactile sensing). That is, measuring the direction of 'tipping susceptibility'.

(c) Transport of the peg in that direction under loose confinement to assembly.

These stages were then discussed qualitatively and quantitatively.

(iii) Experimentation was carried out to verify this concept. A test jig was built to test the method of hole direction search. The concept was shown to be practicable and performance data were collected for that particular implementing mechanism.

Even though this work professes to aim at a mid-range solution to the robotic assembly problem, at this level of research, the findings are, in fact, quite general. The work of Part One on problem definition, and that of Part Two on the mechanics of contact, reaction forces, chamfers, and loose confinement transport, are all indifferent towards any particular policy of solution. Even some of the tactile alignment methods discussed in Part Three may find a place in an essentially non-tactile system of solution. For example, for very slightly constrained input conditions (poorly defined component positions), the faculty of sight may be used for long range sensing and short ranged tactile feedback may be called upon for sensing at the assembly interface.

It was said that the experimentation was limited in anticipation of the completion of a general purpose, computer-driven testing 'robot'. When this facility becomes available the entire three stages of the Invariant Planes Contact solution (and any other solution proposals) can be fully tested and evaluated.

In the 'tipping susceptibility direction' sensing mechanism, an improvement would be the succession of the finite roll-tipping detector by a 'rigid' system which measures the strain produced by the manifested tipping moment. This would help remove any positional errors due to the finite displacements now associated with the rolling. With the use of the above mentioned test robot, the problem of moment application (for testing the susceptibility to tipping) will not arise as it will be provided by the robot hand.

Obviously, this project only covered a very small area of the entire spectrum of assembly problems. It examined the process of cylindrical peg-hole assembly, investigated in greater detail the nature of contact forces, and its implications for tactile sensing, and suggested some solutions to this specific peg-hole problem. Further areas for study in this line may concern rectangular sectioned assemblies, the placing of washers onto pegs, etc. with the common aim of broadening the knowledge of assembly mechanics. It is hoped that the faculty of tactile sensing could be made the common factor that will bridge this eventual knowledge to give a repertoire of solution techniques for robotic assembly.

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